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RATE OF SPREAD OF SURFACE FIRES IN THE PONDEROSA PINE TYPE OF CALIFORNIA ©

By

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and
Wallace L. Fons, Assistant Engineer
California Forest and Range Experiment Station

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RATE OF SPREAD OF SURFACE FIRES IN THE PONDEROSA PINE TYPE OF CALIFORNIA

By John R. Curry, Senior Silviculturist and Wallace L. Fons, Assistant Engineer, California Forest and Range Experiment Station 1/

Studies of forest fire behavior have as their broad objective the determination of the natural laws governing primary ignition and subsequent rate of spread of fires in forests and in related types of inflammable vegetation. The purpose of such studies is to provide an improved foundation for fire control, a major activity in American forestry. Scientific evaluation of the factors affecting fire behavior cannot replace experience gained in fire control operations. Such research can, however, supplement experience by providing information not obtainable on the fire line and, by explaining observed fire phenomena, make them more understandable and predictable. Fire behavior studies are needed to give information essential to the extension of methods of forecasting fire danger, to permit determination of size-of-crew and speed of attack requirements, and, finally, to promote development of fire suppression tactics and strategy.

Gisborne (3),2/ Stickel (9), Nichols,3/ and others have studied forest-fire ignition hazard through the determination of variations in fuel moisture content under varying weather conditions, relating these moisture variations to ignitibility through tests with various firebrands. Through the work of these investigators we know that with ordinary firebrands — as matches, smoking materials, and small campfires — ignition occurs only when the forest fuels contain moisture amounting to less than 30 percent of the dry weight of the fuel. These studies have also resulted in an understanding of the influence of meteorological factors on moisture variations in the fuel, permitting estimation of moisture from a knowledge of weather factors.

1/ Maintained in cooperation with the University of California at Berkeley, California.

2/ Figures in parentheses refer to Literature Cited, page 38.

3/ Nichols, L. H. The burning of setters' slash and meteorological conditions in the province of Quebec during 1931. The Quebec Forest Industries Assoc., Ltd., 4th report, 22 pp., illus,, 1931. (Mimeographed.)

Show (6) first studied rate of spread in 1916 and 1917, using small test fires. As a result of observations made on 33 fires during this period, he concluded that fires burning under conditions favorable to rapid spread tend to burn with acceleration, while slower-burning fires tend to burn at a steady rate. His observations also led him to conclude that the effect of wind could be expressed as a function of the square of the wind velocity. Through theoretical analyses of the factors influencing combustion in the open, Hawley (4) and Gray[4/] have contributed in a major way to the advancement of fire-behavior knowledge. Show and Kotok, in analyzing the California fire records, have broadly defined the influence of cover type (8) and weather factors (7) on rate of spread. These studies have resulted in determination of the speed of attack required for effective suppression under hazardous conditions.

The present study may be considered a continuation of the work begun by Show in 1916. The primary purpose of both studies was the exploration and definition of the relationships between fuel, fuel moisture, weather factors, and rate of spread. Pure stands of ponderosa pine were chosen for these experiments because it was the simplest fuel type available and because it is an extensive and commercially important timber type. By initiating studies in a simple type, it was considered probable that relationships would be developed of value to the extension of rate of spread information to other more complex types.

DETAILS OF STUDY

Selection of Variables

Studies of fire behavior are made complex, first, by the number of factors involved and, second, by the variation found in these factors from place to place and from time to time within the forest. Wind normally fluctuates widely both in intensity and direction and this characteristic is intensified in the forest by the resistance offered by the foliage and tree trunks. Fuels in themselves vary widely from place to place within the stand, and the moisture content of fuels is constantly changing with changes in weather conditions.

Six primary factors are recognized in rate-of-spread studies, viz: (1) Fuel size and arrangement; (2) moisture content of the fuel; (3) air supply (wind movement); (4) slope of the ground; (5) the tendency of fires to burn at an increasing rate, or the effect of time; (6) size of the fire. The first five factors listed are independent variables while the sixth is the variable under study, or the dependent variable. Although other important variables may be defined by further research as affecting fire spread, the problem may at this stage be considered essentially one of relating rate of increase in fire size to concurrent variations in the five other variables listed.

4/ Gray, L. G., Preliminary report on fire hazard rating study. U. S. Wea. Bur. mimeographed report, 54 pp. illus. San Francisco.

Present knowledge of the factors influencing combustion in the open contains no information on methods of measuring one factor, variation in the physical characteristics of forest fuels. Hawley (4) has suggested the use of the surface-volume ratio as an approach, but the specific technique of measuring this, or any other fuel factor which might be used to explain rate of spread fluctuations, remains to be developed. This lack of a well defined theory and technique for the measurement of the fuel variable made it necessary in the present study to eliminate this factor so far as possible. This was the primary reason leading to the selection of the ponderosa pine type, which contains the most uniform fuel conditions to be found in California. Under some situations in this type, usually in dense even-aged stands, the fuels present consist almost entirely of a layer of pine needles from 1 to 4 inches in thickness.

Selection of Sites

Characteristic virgin stands of ponderosa pine were not suitable as sites for this study. They consist of groups of mature and overmature trees interspersed with more open areas occupied with brush, or reproduction of various ages. Litter accumulates to depths of 4 to 5 inches within the dense groups, while a few feet away, in an opening between groups, the ground may be bare. Such fuel conditions were too uneven to meet the study specifications.

Only two kinds of stand within the type were found with sufficiently uniform surface fuel. Optimum conditions were found within certain even-aged dense stands of ponderosa pine on the Shasta experimental forest, usually 45 to 50 years of age, and averaging about 600 trees to the acre, with an average diameter breast high of 9 inches, and a height of 60 feet. (Fig. 1.) Certain uniform relatively dense even-aged virgin stands in which the younger trees had been killed by light fires were also found to be well adapted to the study. The generalizations made in this report as to surface fires in the ponderosa pine type should therefore be construed by applying specifically only where the fuels conditions are uniform; that is, where the ground is completely covered by at least one inch of pine needles.

Fortunately for the simplification of the first year's study, the second-growth stands on the Shasta Experimental Forest occurred on level ground, permitting the elimination of slope as a variable and reducing the number of variables to be measured to four, viz: (1) Size of fire; (2) moisture of fuel; (3) wind velocity; and (4) effect of time. In all, tests were conducted on 13 carefully selected sites during the first year's study. During 1934, the fires were confined to 2 sites and included studies of fires on sloping ground.

Figure 1.- A typical even-aged stand of ponderosa pine, showing the uniform fuel conditions sought in the experiments.

Conduct of Tests

The primary factors measured on each fire were fuel moisture, wind velocity, perimeter at each 2-minute interval, and, where important, slope. In addition, several secondary factors were recorded, as depth of litter, air temperature, surface fuel temperature, relative humidity, and barometric pressure.

For the plotting of perimeter, steel stakes were set at 5-foot intervals on lines radiating from the central ignition point. With these stakes in place it was practical for the plotter to enter the perimeter of the fires directly on polar coordinate paper. Figure 2 illustrates a fire 8 minutes after ignition on a typical test plot. Plotting was ordinarily done on a sketching tripod, as shown.

Samples for moisture-content determinations were gathered immediately before the start of the fire. Two methods were used at different times during the tests. The first consisted of gathering two samples, one in an open exposed part of the test plot, and a second in a more dense, covered portion. By the second method a single sample was taken of the top needles over the whole plot. Because rather wide variations were found over the plots, the average moisture value proved the most useful. Samples were collected in friction lid cans and were weighed the day of collection. Because of lack of facilities in the field, all moisture determinations were made at one time, at the end of the field season. The initial moisture determinations were based on ordinary oven-drying procedure. Later, studies by Buck (1) and Hughes led to the use of a more accurate and speedy xylene distillation method. Moisture percentages used in this report have all been reduced to the xylene distillation standard, which is about 1.5 percent higher in indicated moisture content than originally computed on an oven-dry basis.

The measurement of wind velocities on the test fires presented problems in the selection of an instrument and in the choice of height above ground surface at which the measurement would best represent the influence of wind on rate of spread. Wind velocities within closed stands are relatively light in comparison to concurrent velocities in the open, but nevertheless have a great influence on rate of spread. The ordinary 3-cup anemometer was found to lack the sensitivity required for measuring these light winds. The Biram type (fig. 3) is much more sensitive and was used on all fires studied. To adapt this anemometer to the study of test fires, it was mounted on bearings, and provided with a vane to maintain its axis parallel to the wind direction. So adapted, this type is recommended for all similar studies. An anemometer on the hot-wire principle was tried later, but produced records no more useful than those obtained with the Biram type. After some experimentation, 30 inches above ground surface was selected as the desirable standard height for measurement of wind velocities and throughout the study the anemometers were so mounted. Although an automatic recorder was developed toward the end of the experiment, the data used in the analysis consisted entirely of velocities recorded visually each 30-second interval over the period of the tests.

Figure 2.- Test fire in ponderosa pine 8 minutes from ignition.

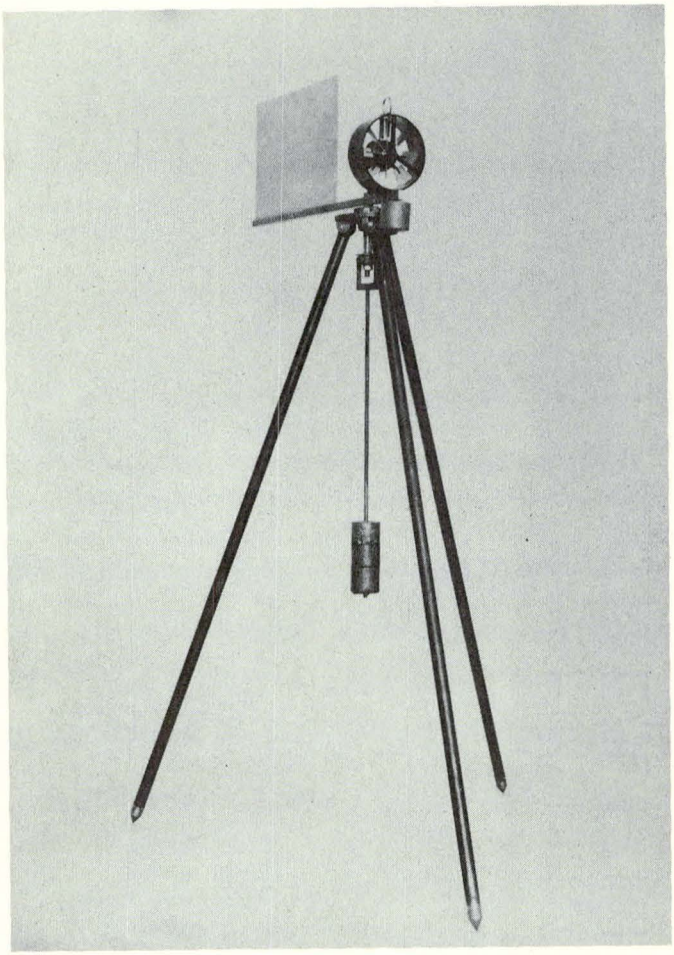

Figure 3.- Biram (vane) type anemometer mounted on a special tripod and fitted with a large direction vane.

Time records were taken with stop watches from the instant the match was applied. On a portion of the fires, temperatures attained by the fire during combustion were measured with thermocouples. Records of air temperatures, litter temperature, relative humidity, and barometric pressure were obtained with standard instruments. A detailed description, including needle depth, crown density, openings in the canopy, and size of trees was made for each plot. A running description of the behavior of each fire was a part of the routine observations.

On the smaller fires, one man plotted perimeter, a second recorded wind movement, while a third made a running description of the fire. On the larger fires the number of men was increased to a maximum of 7, to allow more men for recording wind velocity, plotting perimeter, and for operating the thermocouple apparatus.

In the test-fire procedure, after the selection of the test plot by the chief of party, a crew set the lines of stakes, using compass and tape, and taking care to disturb as little as possible the natural condition of the surface litter. While this work was proceeding, another crew removed from the plot all large limbs and other debris which might influence the spread, and trimmed low dead branches which might tend to make the fire crown. In the early experiments, fire lines were cleaned around the test plots, but this practice was later abandoned, since the lines were seldom used, their preparation required considerable time, and their use reduced the number of plots which could be studied on any one site.

During the process of plot preparation, the plot description was made, emphasizing any abnormal or unusual features; record forms were prepared, and the anemometer set up to windward within 10 feet of the estimated reach of the fire line. Thermometers were exposed in the litter, to be read just prior to the start of the fire.

Fire-fighting equipment was then assembled, water supplies inspected, and the suppression crew distributed. At this point a check on the progress of all preparations made it possible to set a time for the start of the fire. The final records, temperature, humidity, and litter moisture were taken within a 5-minute period preceding the starting time.

The fire was started by applying a single match at the center stake and simultaneously the stop watches of the observers were started. Thereafter all records of wind, perimeter, and fire behavior were maintained according to stop-watch readings. Perimeter was recorded on the smaller fires at each even 2-minute period. On larger fires it was found desirable for the plotter to travel continuously around the fire marking the perimeter location and the time of observation to the second. The accumulated total wind movement was read at each 30-second interval.

At the conclusion of the test, the fires were stopped by the application of water. With the edge of the fire dead, the smoldering litter was systematically extinguished to the center. By fast, thorough action it was usually possible to extinguish a test fire completely and to clear a fire line to mineral soil around it within 20 minutes of the end of the study. With experience, it was possible to obtain from 2 to 5 tests a day, depending on the area of the fires. Test plots were inspected regularly for several days following the fire.

During the 1933 field season, 95 selected test fires were studied on the Shasta Experimental Forest, under uniform conditions in the ponderosa pine type. During this season, the fires were allowed to attain a size of 1/60-acre to 1/40 acre, the maximum size readily extinguishable with the facilities available. The period of study was ordinarily 13 minutes, although some slow-burning fires were allowed to spread for 30 minutes or more. Extremely rapid-burning fires were, for reasons of safety, suppressed at 12 or 14 minutes.

Preliminary analysis of the 1933 records showed that the data would be much improved through additional studies over a longer total burning period. Some data on the effect of slope were also desired. In 1934 an area in ponderosa pine was selected on the Lassen National Forest, 100 miles south of the 1933 center of work, and here 69 fires were set, 46 of these being on slopes above 10 percent in grade. During this second season, the tests ran for 30 minutes on the 23 fires on level ground. These fires attained areas of 0.05 to 0.5 acre. The suppression problem was increased to an extent sufficient to reduce materially the number of fires studied.

GENERAL CHARACTERISTICS OF THE DATA

A cursory examination of the data available at the completion of the tests revealed large fluctuations in rate of spread at different hours of the day. A fire at 7 A. M. might reach a perimeter of 25 feet in a 12-minute period and later on the same day another might attain 150 feet during the same burning period. Even average values fluctuated widely with time of day, as shown in table 1.

The summer climate of northeastern California is remarkably uniform. During the period of these tests, little or no precipitation occurred and clouds were uncommon. Minimum temperatures at night ranged from 30° to 55° F., while maximum day temperatures were within a range of 70° to 90°. Relative humidities in the summer at this elevation (4000-5000 feet) vary from 100 percent in the early morning hours to a minimum of 10-11 percent in the early afternoon.

One striking fact illustrated by table 1 is the average low wind velocity recorded on these fires. From this it might be inferred that the tests were conducted purposely at times of light wind. In fact, however, windy conditions were sought rather than otherwise, but velocities within the stands were seldom greater than 3.5 miles per hour and

Table 1.- Hourly averages of rate of spread factors.

1933 - 1934 Fires.

Hour of day	Fires	Area in 12 minutes	Perimeter in 12 minutes	Wind velocity	Moisture content	Relative humidity	Air temperature
	Number	Sq. ft.	Feet	M.p.h.	Percent	Percent	° F.
7:00 A.M.	1	60	30	0.0	12.5	45.0	72.0
8:00	6	95	36	0.3	10.0	60.8	58.7
9:00	12	164	44	0.9	9.9	42.9	66.9
10:00	21	285	62	2.1	9.1	31.8	73.7
11:00	14	320	66	1.7	8.6	28.4	75.5
12:00	2	295	64	1.2	7.6	22.5	83.0
1:00 P.M.	14	476	84	2.0	7.0	22.2	83.2
2:00	17	458	80 — 400'/hr. 6ch./hr.	2.0	6.6	22.9	81.4
3:00	11	328	67	1.3	7.1	22.8	81.9
4:00	11	257	60	1.1	6.8	23.3	82.5
5:00	3	212	54	0.6	6.9	31.7	78.3
6:00	2	104	38	0.0	8.0	48.5	68.0
7:00	1	133	42	0.5	8.3	53.0	68.0
8:00	2	166	48	0.8	9.0	54.5	66.5

then only for short periods. This was due to high efficiency of the timber as a windbreak. It can be stated as a result of these observations, and on the strength of further studies by the authors, that winds near the ground in moderately dense stands seldom attain a velocity greater than 3 miles an hour even when in the open they reach 30 or more miles an hour.

The tendency illustrated in the table for high wind velocity and low moisture content to occur during the same periods was noted in conducting the tests. Although such intercorrelation is undesirable for the purpose of analysis, there appeared to be no practical method of correcting this condition. Wind in the area where the tests were located is largely controlled by thermal convection, with the strongest movement during that part of the day when air temperature is highest. Absolute humidity tending to remain constant, the moisture content of light fuels in the areas studied responded quickly to changes in temperature. While this phenomenon is undoubtedly characteristic of other forests, it is particularly pronounced in the summer climate of interior California where air conditions are characteristically stable.

The average moisture contents of litter shown in table 1 range from 6.6 to 12.5. The total range on these plots was from 4.0 percent to 13.5 percent. Since all fires were studied during a period when rain had not fallen for several weeks, it may be assumed that these variations are the result of diurnal fluctuations in atmospheric conditions.

The accompanying charts, figures 4, 5, and 6, illustrate characteristic types of perimeter records. The lines on the chart represent the margin between flames and unburned litter at successive 2-minute intervals. On the slower fires the width of the flaming area was about 6 inches, but on fast fires the flames might attain on the leeward side a width of several feet.

The simplest type of fire is that shown in figure 4, where air movement is too light to affect spread appreciably. Such a fire soon develops into a thin ring of fire with the flames turning inward and upward as shown in figure 2. This tendency of flames to burn inward is due to the displacement of the hot gases rising from the smoldering interior by cool air from outside the ring of fire. In the absence of changes in fuel conditions, fuel moisture, and wind, the rate of spread of such a fire would vary only during the period when the fire was becoming established, and with changes in the indraft due to variations in the volume of rising gases. The regularity shown in the burning rates of fires of this type gave support to the assumption of uniform fuel conditions.

The chart of a fire burning under a wind of constant direction and under comparatively uniform velocity is shown in figure 5. Although fires starting under these conditions are at first not greatly affected by the wind, they spread much more rapidly after becoming established. The shape of the fire and the rate of spread are in this case very noticeably affected by a wind of an average velocity of 2 miles per hour.

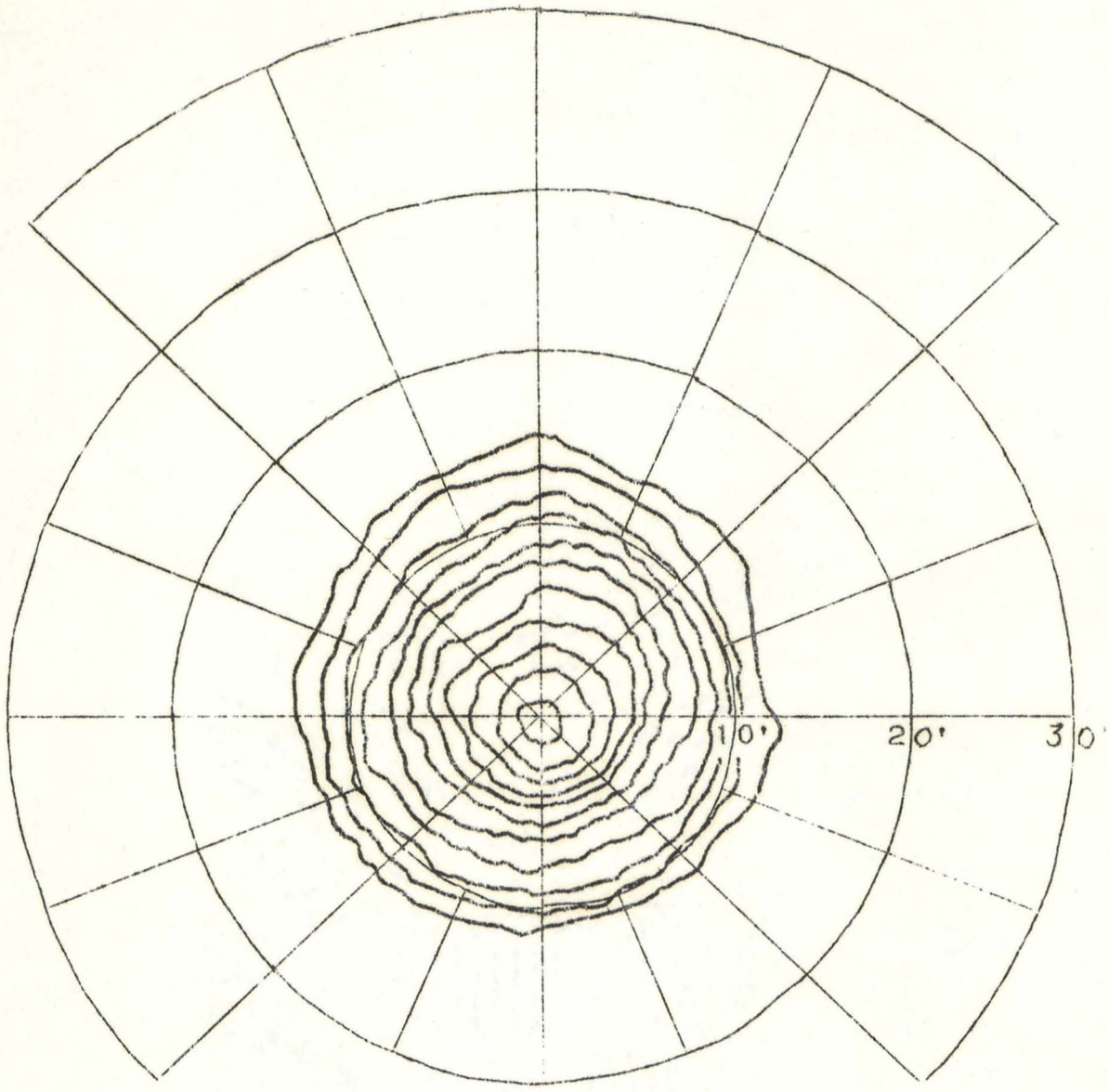

Figure 4.- Diagram of slowly spreading fire. Average wind velocity 0.2 m.p.hr. Fuel moisture content, 7.0 percent. Perimeter shown at each 2-minute interval.

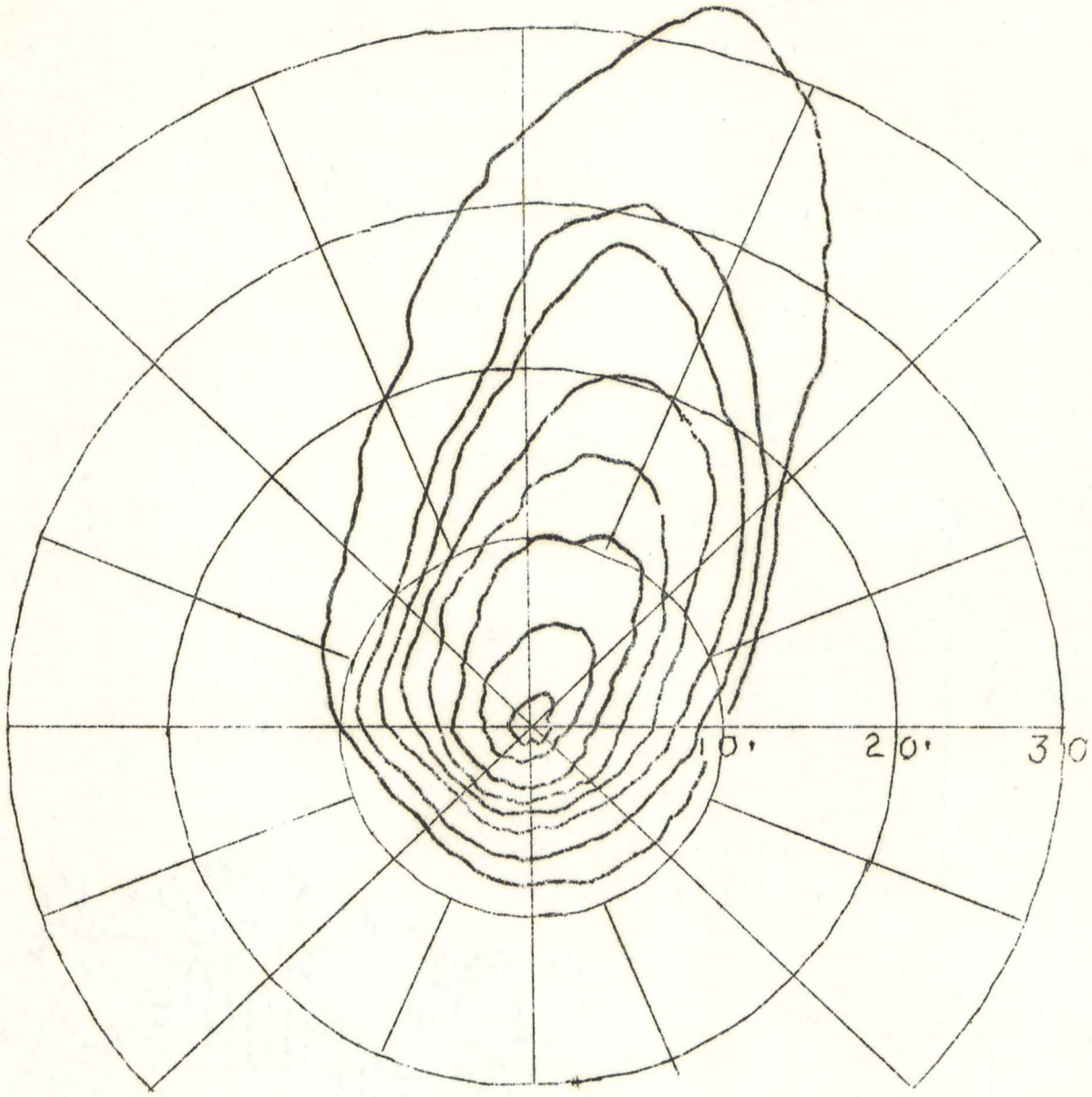

Figure 5.- Diagram of rapidly spreading fire with constant wind direction. Average wind velocity 2.0 m.p.hr. Fuel moisture content 4.3 percent. Perimeter shown at each 2-minute interval.

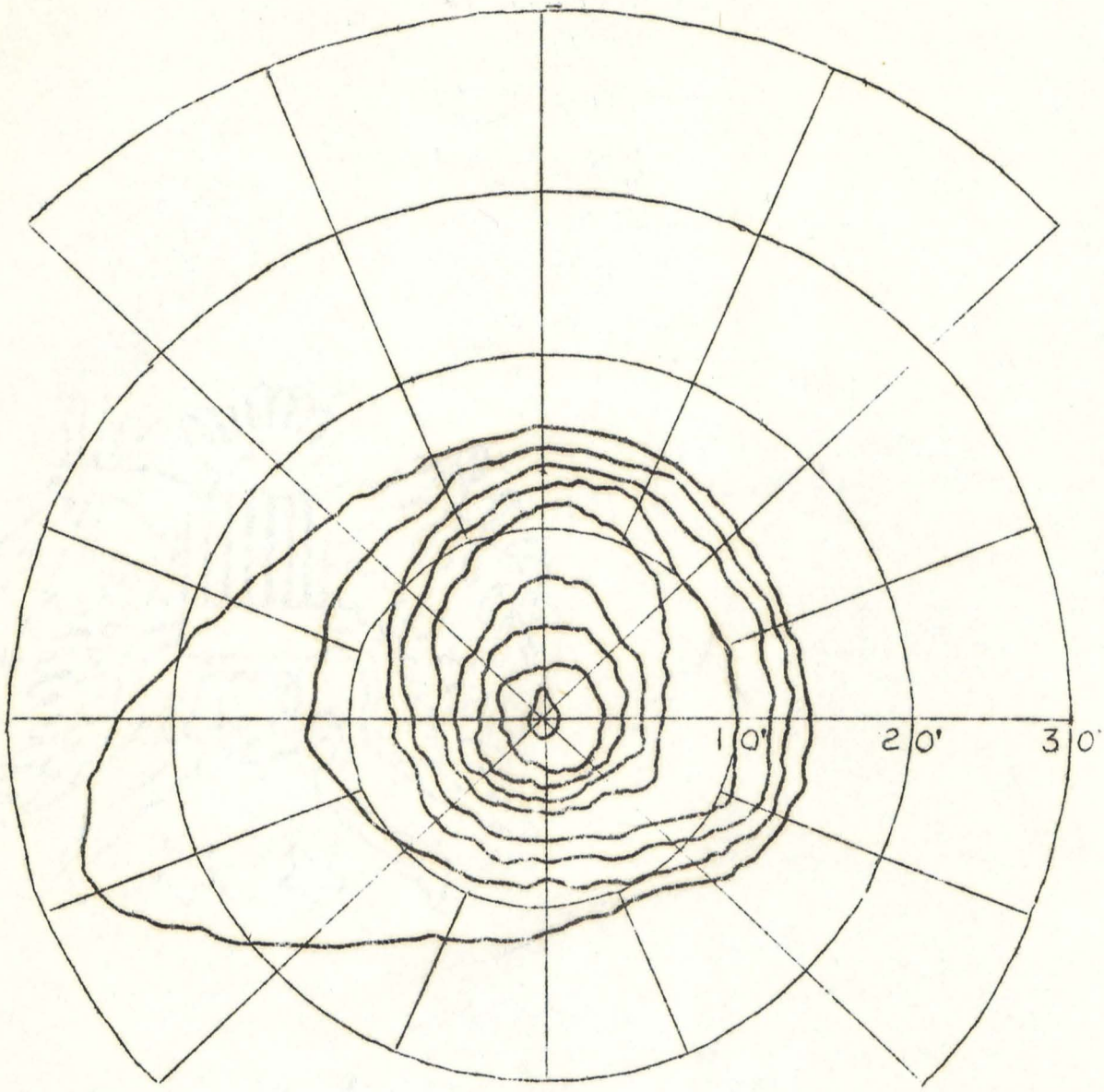

Figure 6.- Diagram of rapidly spreading fire with variable wind direction. Average wind velocity 1.1 m.p.hr. Fuel moisture content 9.0 percent. Perimeter shown at each 2-minute interval.

Figure 6 illustrates a somewhat different type of fire, one more characteristic of normal conditions than those shown in the two preceding charts. In this case the wind movement varied both in rate and direction. Fires behaving in this manner increase their area more rapidly than fires burning with a comparable velocity in one direction only. The effect on perimeter of such variation is, however, unimportant.

With a wind of more than 1 mile per hour, the influence on the size and shape of the flames is immediately noticeable. Flames on the leeward side increase in size and turn outward, becoming with higher velocities approximately parallel with the surface of the ground. On the windward side, the flames are reduced in intensity and driven toward the burned area. On the flames burning at right angles to its direction, the wind has apparently little effect.

METHOD OF ANALYSIS

The first step in the analysis consisted of measuring the perimeter and area increase from perimeter charts such as those shown in figures 4 to 6. Perimeter was obtained with a map measurer and checked to the nearest foot. Area was obtained through the use of a planimeter, to the nearest square foot. These data together with the corresponding data for wind velocity, moisture content, and time for the 118 fires on level ground were then entered on 1,153 cards, each containing the complete record of one 2-minute interval. Because of the scarcity of data in the higher time classes, all cases above 22 minutes were eliminated. Although both perimeter and area were entered on the cards, perimeter only was used in the analyses. The area of a circle, or an ellipse, increases in proportion to the square of its radius, while the perimeter increases in direct proportion to the radial increase. The rate at which the area of a fire increases is, consequently, a function of the size of the fire, while the rate of perimeter increase is, geometrically speaking, independent of size. Furthermore, perimeter is of greater significance in fire control, as better representing the suppression effort required.

Mathematical methods of multiple linear correlation were first used in an attempt to define the combined relationships. Two difficulties were encountered, however: first, the relationships so derived are linear, whereas it was considered probable that the relationships were in part curvilinear; second, this form of analysis is unsuited to definition of relationships where joint correlation exists; that is, where the influence of any one independent variable on the dependent variable is affected by the size of another independent variable. Show (6) discovered the presence of joint correlation in his 1916 data and preliminary curves in the present analysis confirmed this finding: consequently, methods which would permit the definition of joint correlation, if it existed, were desirable. These considerations led to the use of methods recommended by Ezekiel (2) for problems of joint correlation. Inasmuch as these methods led to the final conclusions, they are explained in detail.

First, all cards were sorted into 2-minute time groups. Next, the cards in each time class were sorted into three moisture classes — below 7.4 percent, 7.5-10.4, and 10.5 and more. A third segregation was then made within each moisture class, on wind velocity, five wind-velocity classes being recognized as follows: 0.0-0.9 m.p.h., 1.0-1.9, 2.0-2.9, 3.0-3.9, and 4.0 +. Eleven tables of the type shown in table 2 resulted, one for each 2-minute period.

The next step was to plot the average value of the dependent variable (perimeter increase) on the average values of wind as a first approximation of the influence of that variable. Wind was used in the first approximation because preliminary studies had shown its influence to be most strongly defined. Three curves showing the effect of wind on perimeter increase, one for each moisture class, were constructed free-hand for each time interval, a total of 33 curves in all. These curves served as a first approximation of the influence of wind velocity on perimeter increase throughout the entire range of moisture and time conditions.

To determine the influence of moisture, a second series of approximation curves was drawn, using the first curves as a base, with moisture content plotted on the horizontal axis. After these plotted points were smoothed by free-hand, a third approximation was made with time plotted on the horizontal axis. The fourth smoothing was made with wind velocity plotted on the horizontal axis as in the first approximation. Changes in the relationships became smaller at each smoothing and were finally considered negligible after the seventh and final smoothing.

Several correlation studies of this type were made from the data. The results obtained are dependent to some degree upon the first approximation, where the personal judgment of the one analyzing the data is important. Checks on the final results were made by smoothing in one correlation first on wind and in another first on moisture. While the variations obtained in the final curves were not great, it was desirable to eliminate them if possible.

As anticipated, joint correlation existed in the data and was particularly noticeable in the change in the slope of the curves of wind velocity with increasing time. Some changes were also noted in the slope of the moisture curves with variations in time. On the other hand, no tendency for the slope of the moisture-perimeter curves to vary with changes in wind velocity, or vice versa, was found in any of the several correlation studies made. This and the fact that the influence of both wind and moisture were established by these studies as linear led to a slightly different type of analysis.

Table 2.- Summary of values of wind velocity, moisture content, and perimeter for first 2-minute period;1/ basis - 118 fires on level ground.

Class value X_2	N	Total X_1	Mean X_1	Total X_2	Mean X_2	Total X_3	Mean X_3
For class value X_3 = 0.0 - 7.4							
0.0 - 0.9	12	94	7.8	8.7	0.7	61.7	5.1
1.0 - 1.9	23	203	8.8	31.7	1.4	112.9	4.9
2.0 - 2.9	5	43	8.6	11.5	2.3	21.7	4.3
3.0 - 3.9	4	44	11.0	14.3	3.3	16.9	4.2
4.0 +	4	42	10.5	19.0	4.8	19.3	4.8
For class value X_3 = 7.5 - 10.4							
0.0 - 0.9	23	147	6.4	9.3	0.4	169.0	7.3
1.0 - 1.9	20	137	6.8	26.7	1.3	152.3	7.6
2.0 - 2.9	11	81	7.4	26.8	2.4	77.1	7.0
3.0 - 3.9	1	8	8.0	3.2	3.2	6.3	6.3
4.0 +	3	25	8.3	13.1	4.4	21.6	7.2
For class value X_3 = 10.5+							
0.0 - 0.9	9	46	5.1	1.5	0.2	85.9	9.5
1.0 - 1.9	2	9	4.5	2.3	1.2	18.5	9.3
2.0 - 2.9	-	-	-	-	-	-	-
3.0 - 3.9	1	5	5.0	3.3	3.3	9.5	9.5
4.0 +	-	-	-	-	-	-	-

1/ X_1 = Perimeter increase in feet per two minutes.

X_2 = Wind velocity in miles per hour - average during 2-minute period.

X_3 = Moisture content in percent - based on xylene distillation method.

N = Number of cases.

If joint correlation was not present between the wind and moisture factors, but only between time and these factors, it was apparent that mathematical multiple linear regressions could be obtained for each time interval, thus eliminating personal judgment in the preliminary curving process. The influence of time, a relationship known to be curvilinear, could then be determined by successive free-hand smoothings. This process was followed as outlined, multiple linear regression equations being obtained for the influence of wind and moisture for each 2-minute interval.

At this stage of the analysis a check was obtained on the presence of curvilinearity in the moisture-perimeter and wind-perimeter relationships. Using the methods outlined by Mills, (5) it was determined that no significant tendencies toward curvilinearity existed in any of the 11 correlations.

The next step in the analysis consisted in smoothing the regressions to obtain an expression of the influences of time. This was accomplished in the same manner as has been outlined in the discussion of the preliminary analyses. As a result of this procedure, a higher index of correlation and lower standard error were obtained than where free-hand smoothing methods only were used. After the curves had been defined by successive smoothimgs an empirical formula was derived to express the curves mathematically. This formula and the method of derivation will be discussed subsequently. The analysis of the influences of slope on rate of spread, which was handled in a somewhat different manner, will also be discussed later.

GENERAL RESULTS

As an introduction to the results of the analysis, it may be well to review the theoretical aspects of combustion of wood as summarized by Hawley (4). The ignition temperature of dry wood is approximately 540° F. Inasmuch as the temperature of combustion is in the neighborhood of 1,500° F., it is apparent that combustion of finely divided wood substance will readily proceed, once ignition is established, even in the presence of appreciable amounts of moisture in the fuel. The influence of moisture is explained by the fact that before combustion of wood can take place, all water in it must be raised to 212° F., vaporized, and the vapor raised to the ignition temperature of wood, 540° F. Theoretically the amount of heat produced permits combustion to the point where 5.71 parts of water are present to one part of wood, assuming full utilization of all heat produced in the vaporization of the moisture. From a practical standpoint, however, because of heat loss, wood will not burn even under forced draft if there are more than two parts of water to one part of wood. Under forest conditions, only a small proportion of the total heat of combustion will be available for this purpose. Any considerable moisture content in forest fuels thus slows down combustion, through decreasing the amount of heat available for ignition of nearby fuels.

According to Hawley, at least 133 cubic feet of air are required to burn one pound of wood. This explains in part the influence of wind upon combustion. Wind also influences surface fires by forcing the flames close to the ground surface, thereby increasing radiation to the fuels.

It is common experience that once a fire is established it tends to burn more readily. It has been generally assumed that forest fires rapidly increase their rate of spread with time. In this investigation, an attempt was made to evaluate the length of this establishment period.

In the following discussion, the effects of wind, moisture, and time are treated separately, prior to a discussion of their combined effect.

The Effect of Wind

Smoothed curves showing the effect of wind throughout the range of moisture and wind velocity are shown in figures 7 to 10. The representation of the influence of wind as linear is in disagreement with the conclusions of Show (6). These earlier conclusions are apparently explained by the fact that it was impossible, with the limited data available in the earlier study, to separate the influence of moisture from the influence of wind. The presence of intercorrelation between wind and moisture has been discussed; but this was apparently not taken into account in this early work. In the present analysis, it has been possible to consider the influence of each variable within a small range of variation of the other variables.

A second characteristic of these curves deserving comment is the change of slope with increase in time. At 2 minutes, for instance, rate of spread increases about 0.3 foot with an increase of 1 mile per hour in wind velocity; at 20 minutes the increase is slightly more than 2 feet. The fact that joint correlation does not exist between moisture and wind is shown by the constant slope of the lines for all moisture classes.

The Effect of Moisture

The influence of variations in moisture content of the litter is shown in figures 11 and 12. As in the case of wind velocity, the relationship shown is linear; the slope of the moisture curves is negative. Only sufficient curves are shown to illustrate the general character of the moisture-perimeter relationship.

Joint correlation between time and moisture is shown by the variation in the slope of the moisture curves with changes in time; the variations, however, are less pronounced than in the case of the perimeter-wind curves. Because of this joint correlation, it is difficult to generalize broadly on the influence of the wind and moisture. If any one time is selected, however, a relative comparison of the influence of wind and moisture content is possible. At the 20-minute time interval the influence of 1 percent variation in moisture is approximately 0.4 foot in perimeter. At the same period, the influence of 1 mile per hour in wind

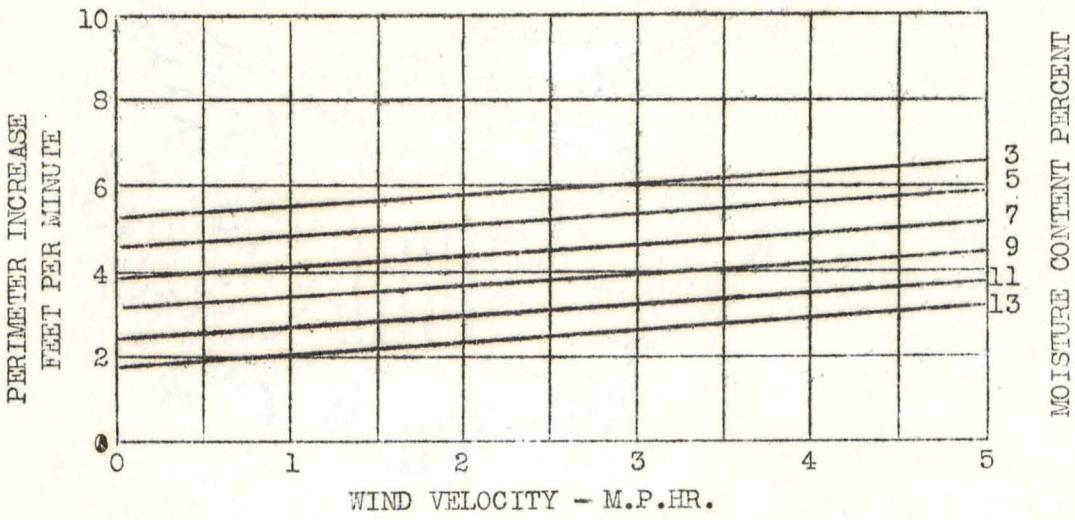

Figure 7.- Probable rate of perimeter increase on level ground for various wind velocities and moisture content at 2 minutes from start of fire.

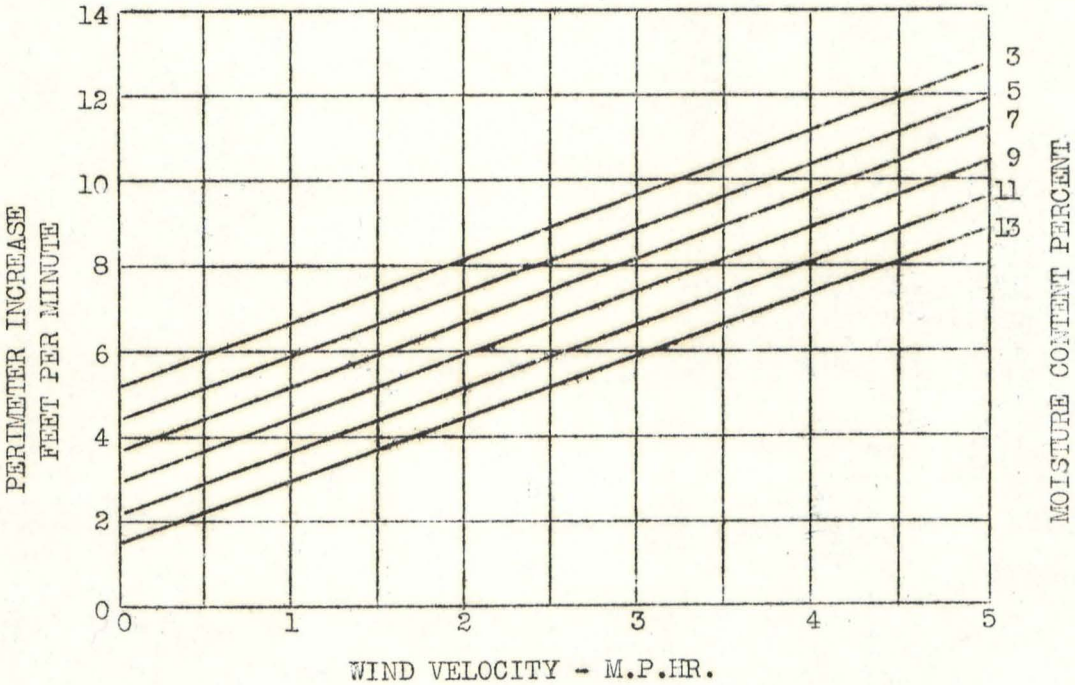

Figure 8.- Probable rate of perimeter increase on level ground for various wind velocities and moisture content at 8 minutes from start of fire.

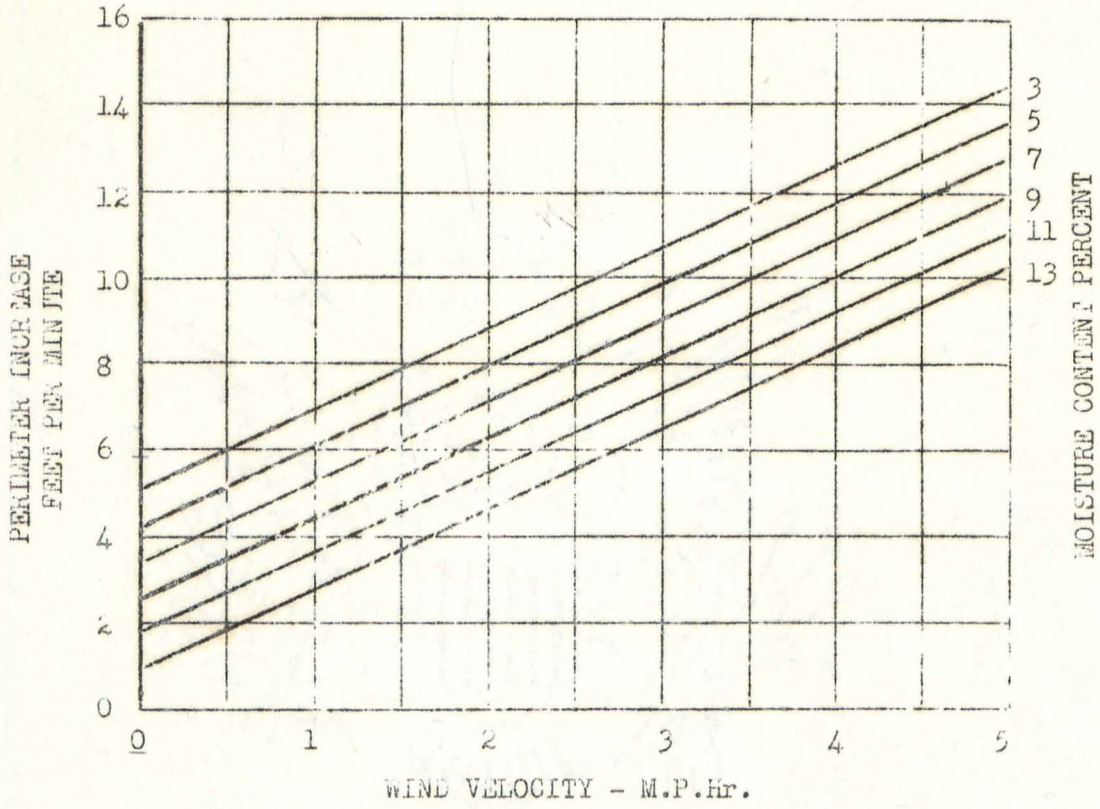

Figure 9.- Probable rate of perimeter increase on level ground for various wind velocities and moisture content at 14 minutes from start of fire.

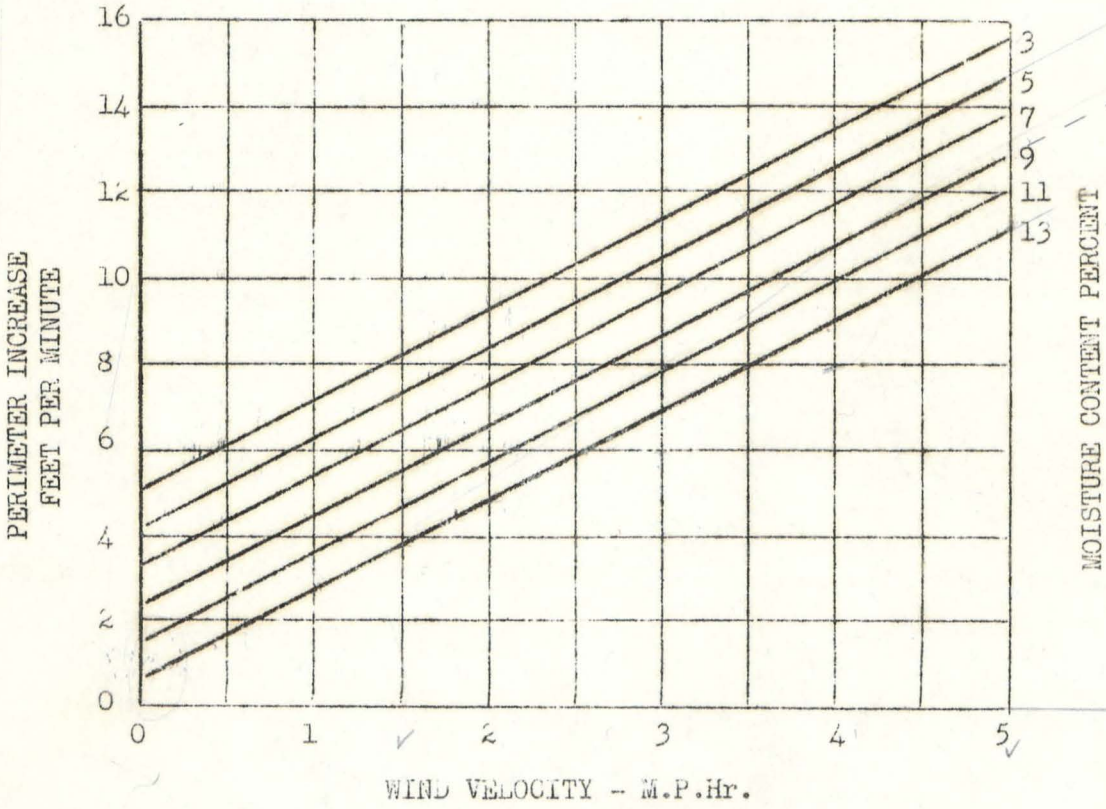

Figure 10.- Probable rate of perimeter increase on level ground for various wind velocities and moisture content at 20 minutes from start of fire.

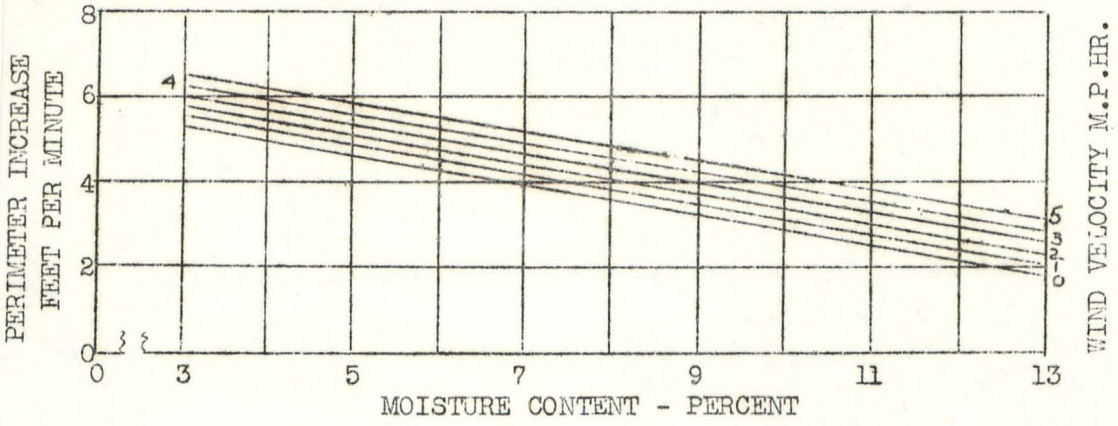

Figure 11.- Probable rate of perimeter increase on level ground for various values of litter moisture content and various wind velocities at 2 minutes.

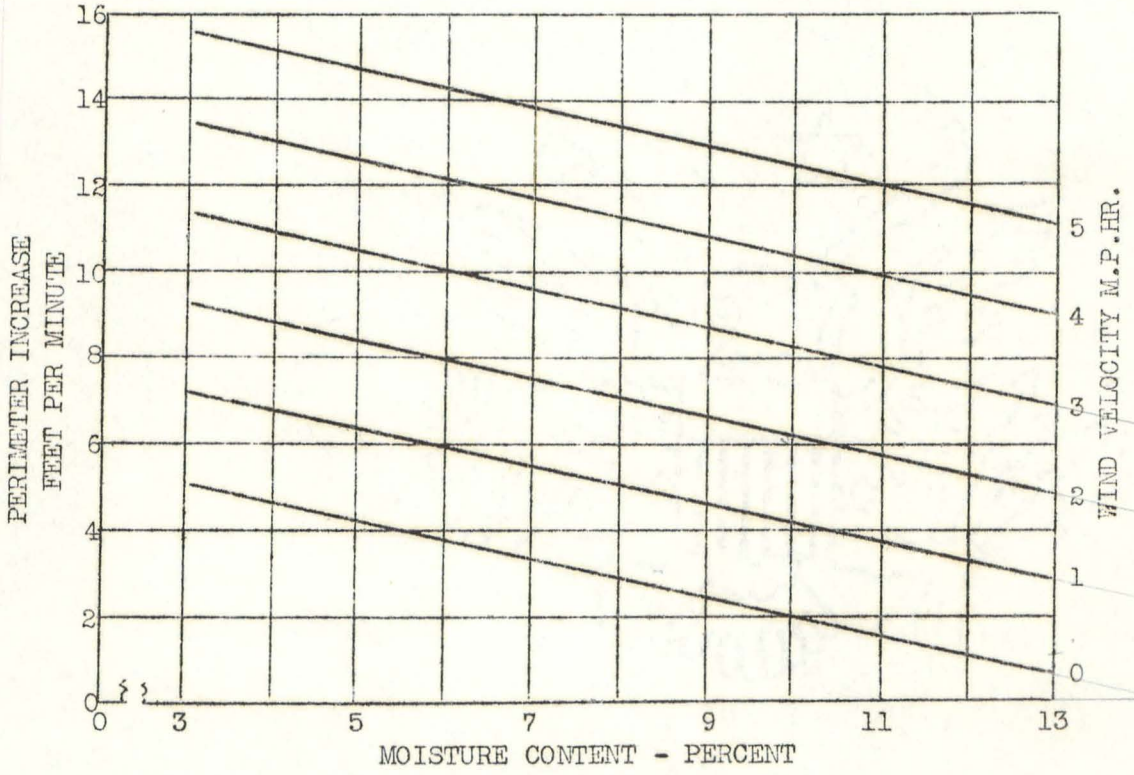

Figure 12.- Probable rate of perimeter increase on level ground for various values of litter moisture content and various wind velocities at 20 minutes.

velocity is 2.0 feet. This ratio of 1 to 5 emphasizes the importance, as defined in this study, of wind on rate of spread, once a fire is started. In making this or similar comparisons, it should be remembered that the wind velocities shown are those measured within the stand, and do not correspond to those measured in the open. A relatively large increase of wind velocity in the open would be required to increase velocity within the stand from 3 to 4 miles per hour.

The Effect of Time

The effect of time on rate of spread, or, as it might be expressed, the tendency of small fires to accelerate their rate of spread under various moisture and wind conditions, is illustrated in figures 13 and 14. Curves are shown for two moisture classes only — 5 and 11 percent. It will be noted that, under low wind, fires tend to assume a constant rate of perimeter increase after the first few minutes of burning. With higher winds, the length of the period over which acceleration occurs increases and at the higher velocities the increase is still appreciable at 28 minutes. Presumably, however, under constant wind and moisture conditions, surface fires of this type would tend at the end of one half hour or slightly more to burn at a steady or only slightly increasing rate.

Combined Influence of Wind, Moisture, and Time

Consideration of the manner in which the three variables — wind, moisture, and time — act in combination to produce various rates of spread is made complex by the presence of joint correlation between time and the other independent variables. In general, it may be said that the influence of both moisture content and time are direct, i.e., linear; and that a variation of 1 percent in moisture will influence the rate of spread by 0.4 foot per minute, while a change of wind velocity of 1 mile per hour will result in a variation in perimeter of about 2 feet per minute. These values are attained, however, only after the fire has burned for some time and they are not constant but vary with the period during which the fire has been burning. Apparently fires tend to reach a constant perimeter increase under unchanging moisture and wind conditions, but the time when this occurs cannot be closely defined from this study. It would appear, however, that the effect of time would be removed in most cases after 30 to 45 minutes. Figures 15 and 16 have been constructed to show the variation in the effect of wind and moisture with time for the span of these tests.

Figure 17 is a drawing of a model constructed to show these relationships simultaneously. In this model, lines cutting through the diagram define the rate of spread values for various values of wind and moisture at a given time period.

The combined influence of wind, moisture, and time on rate of perimeter increase may be more definitely expressed in mathematical terms. From figures 7 and 11, and 8 and 12, it is obvious that the relationships between perimeter, wind, and moisture for any particular time interval,

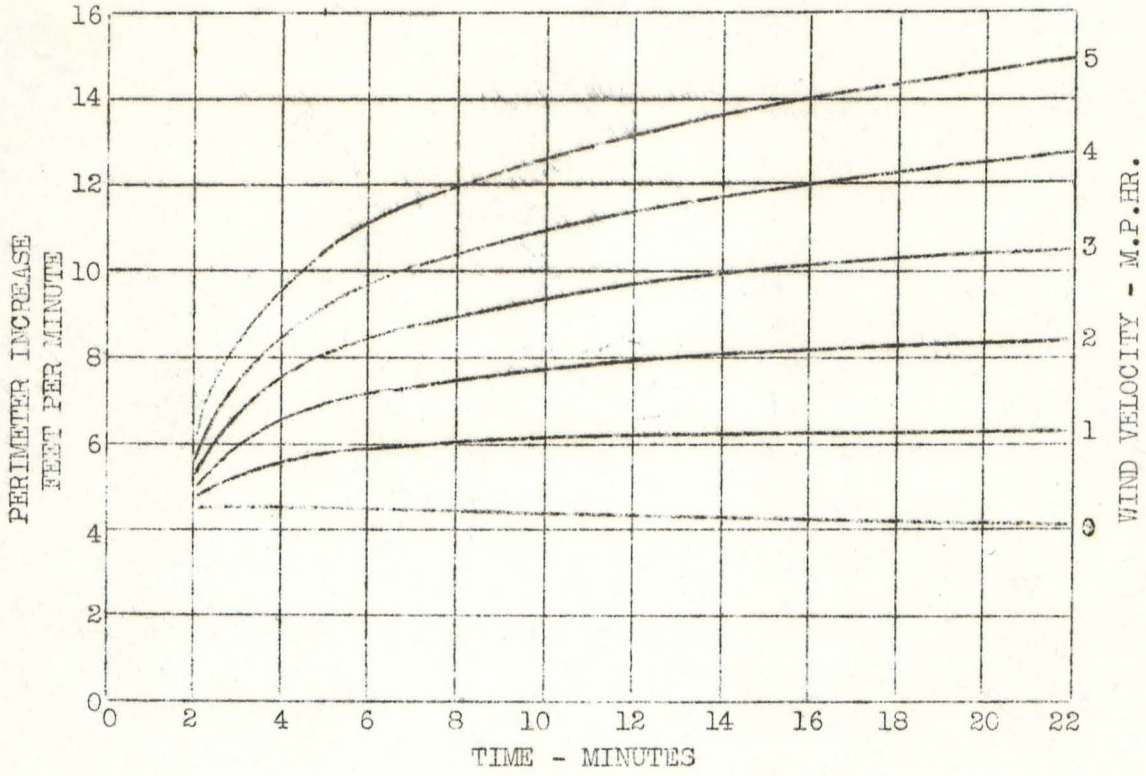

Figure 13.- Probable rate of perimeter increase on level ground at various time from start of fire and at various wind velocities for litter moisture content 5 percent.

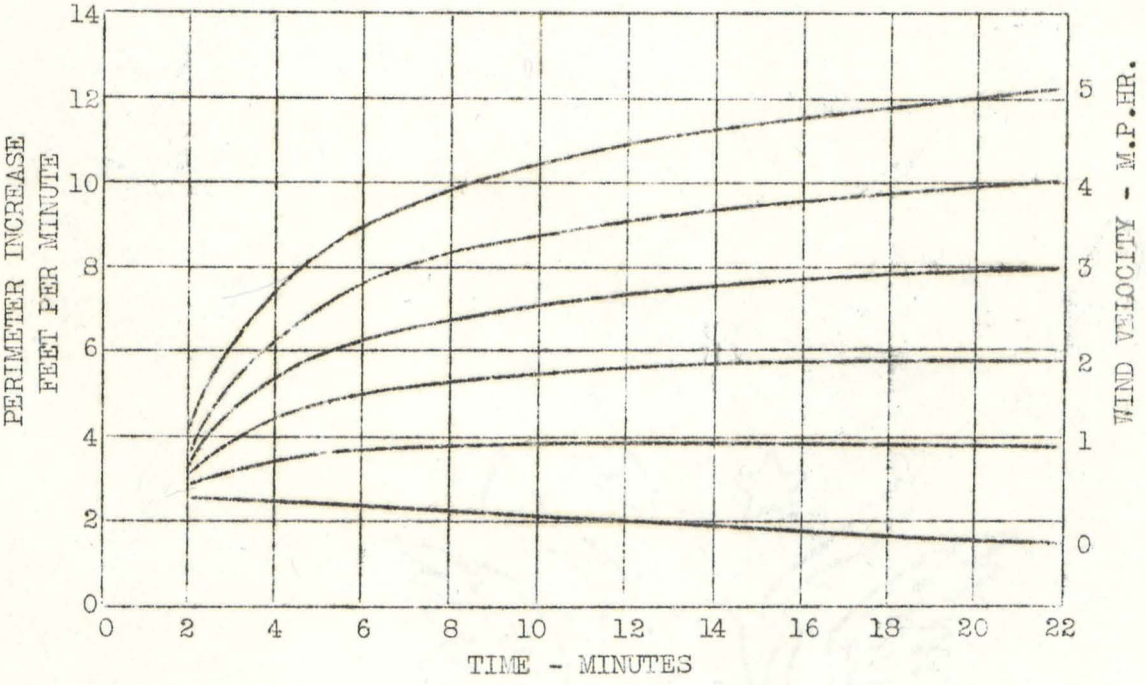

Figure 14.- Probable rate of perimeter increase on level ground at various time from start of fire and at various wind velocities for litter moisture content 11 percent.

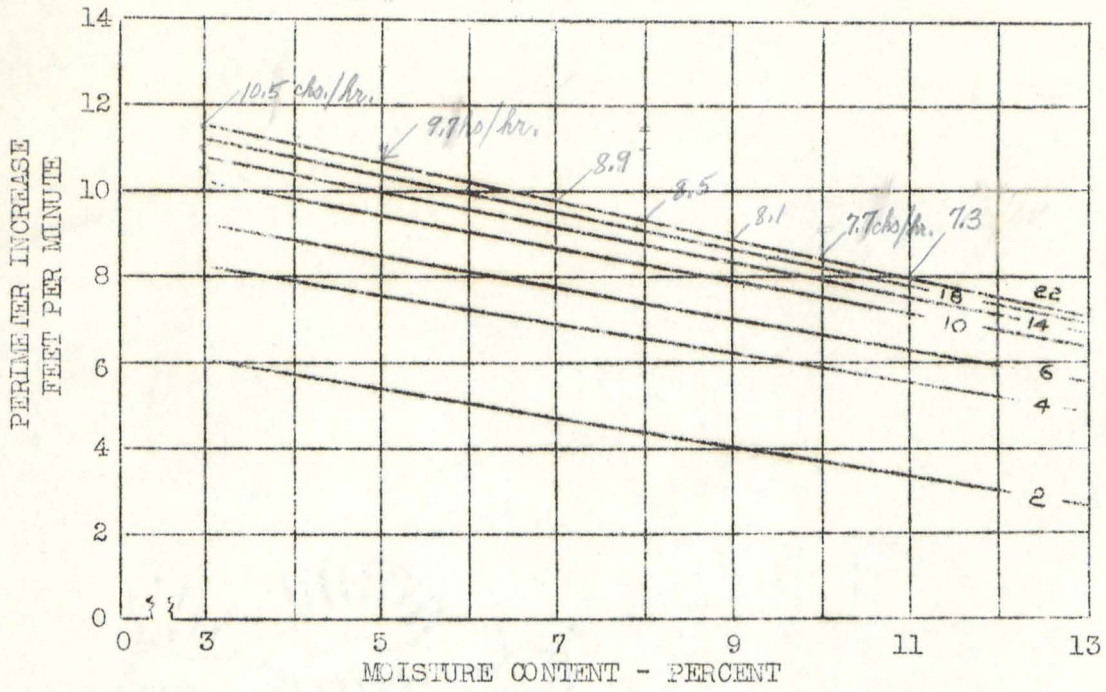

Figure 15.- Probable rate of perimeter increase on level ground for various values of litter moisture content and time from start of fire with wind velocity at 3 m.p.hr.

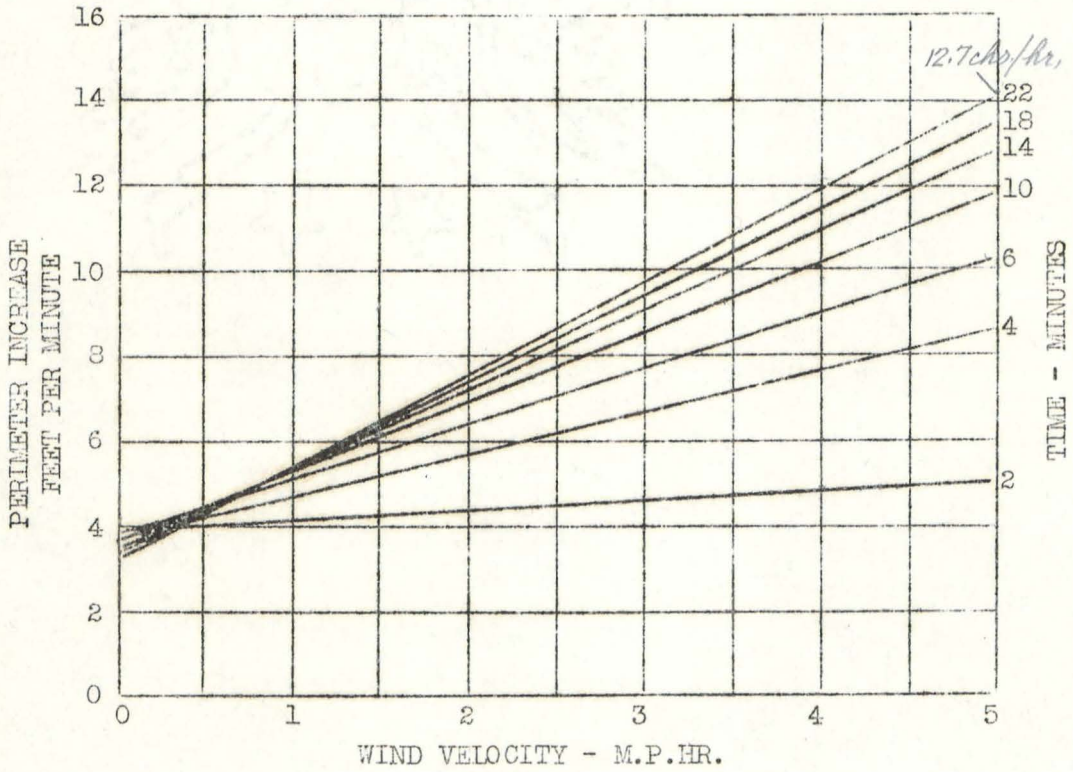

Figure 16.- Probable rate of perimeter increase on level ground at various time from start of fire and at various wind velocities, for litter moisture content 7 percent.

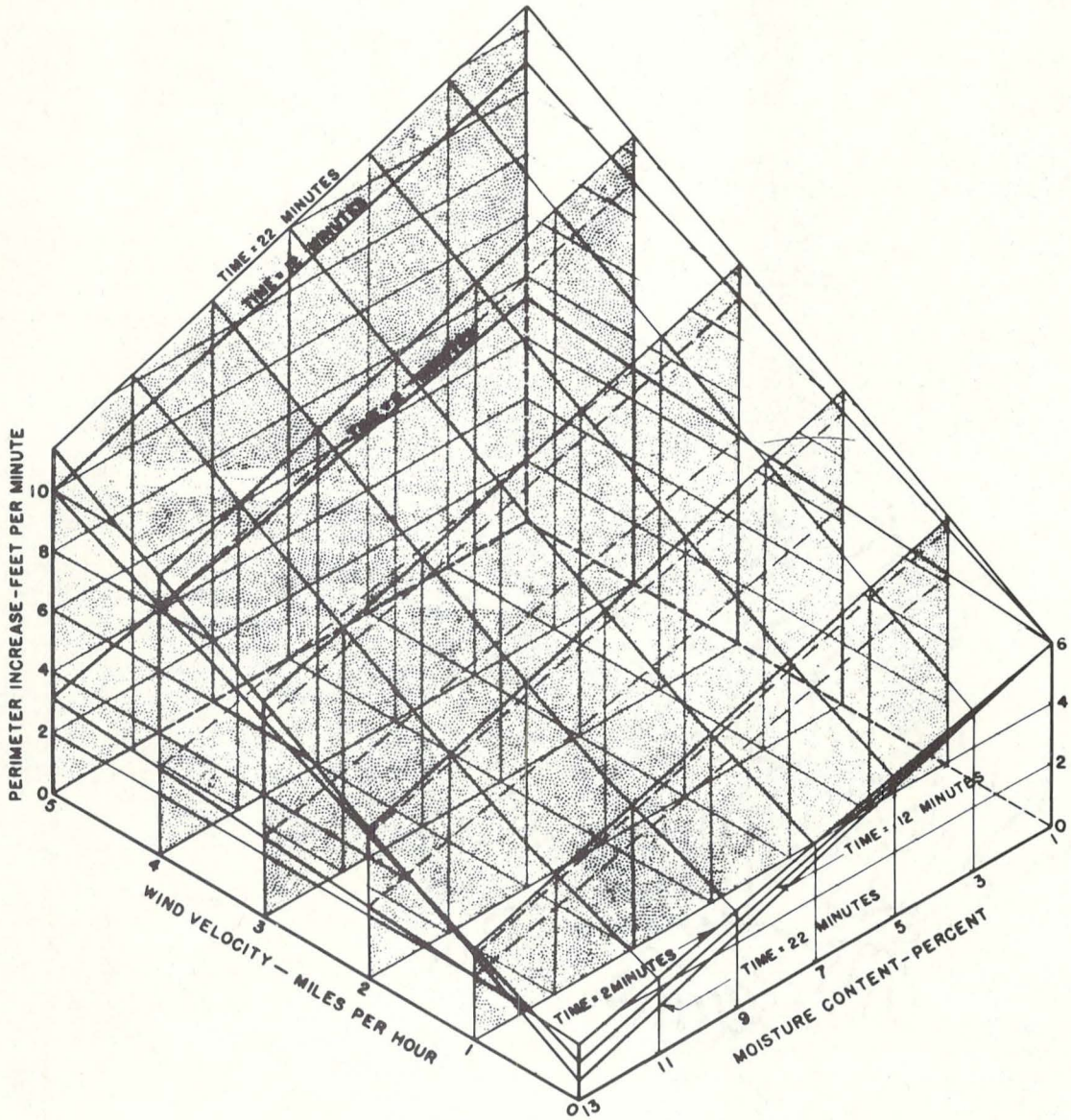

Figure 17.- Chart showing relation between wind velocity, moisture content, time from start, and probable rate of perimeter increase, for surface fires in ponderosa pine needles on level ground.

as 2 minutes, may be expressed by a linear equation of the form

$$p = k - k' M + k'' V \text{ ----------(1)}$$

in which p = rate of perimeter increase in feet per minute.
V = Wind velocity in miles per hour.
M = Moisture content in percent.

The use of the minus sign with the moisture factor is explained by the slope of the moisture-perimeter curve. If formulae are derived for each time period it will be found that the constants k' and k'' will vary as some function of time. If they could be expressed mathematically and introduced into the formula, a mathematical expression of rate of perimeter increase at any time would result.

To do this, values of k' for various times from the smoothed curves were plotted on time. The variation in k' with time is small; in theory it should become constant after a short period. Within the limit of 22 minutes, however, it is practical to treat the relationship as linear, as shown in figure 18. An expression for k' in terms of t is readily obtainable by a linear equation in the form of $k' = a + bt$.

When the values of k'' are plotted on time as in figure 19, the curve resulting is of a more complex type. This may be expressed as a power series of the form:

$$k'' = a + bt + ct^2 + dt^3 + \text{---} mt^n$$

but would have such a large number of terms that its use would be cumbersome.

The value of the constant k may be determined by extrapolation of the smoothed curves to determine the value of p when both M and V are zero. This value, so derived, is 6.35, a constant for any time.

The final equation is:

$$p_t = 6.35 - k' M + k'' V \text{ ----------(2)}$$

in which: p = Rate of increase in perimeter in feet per minute.
t = Time in minutes from start of fire.
k' and k'' = Constants determined from table 3.
V = Wind velocity in miles per hour.
M = Moisture content percent.

At first thought this doesn't seem quite logical. It would seem to be of the form $p = \frac{k(k''V)}{k'M}$ at a given moisture % the O_2 supply may be considered the limiting factor. If the amt. of O_2 supplied per minute is doubled the amount of fuel oxidized per min. will be doubled. The O_2 supplied per min. is proportional to wind vel. if natural draft is small See L. G. Gray's 1933 report p. 26 and 1937 ed. of R-5 Fire Cont. Handbook p. 5 table.

The above [illegible] equa. derived from actual observations may be due to the fact that the wind velocity meas. 30" above the ground and 15' from the fire is not proportional to the draft at the perimeter but is a constant to be added to the draft.

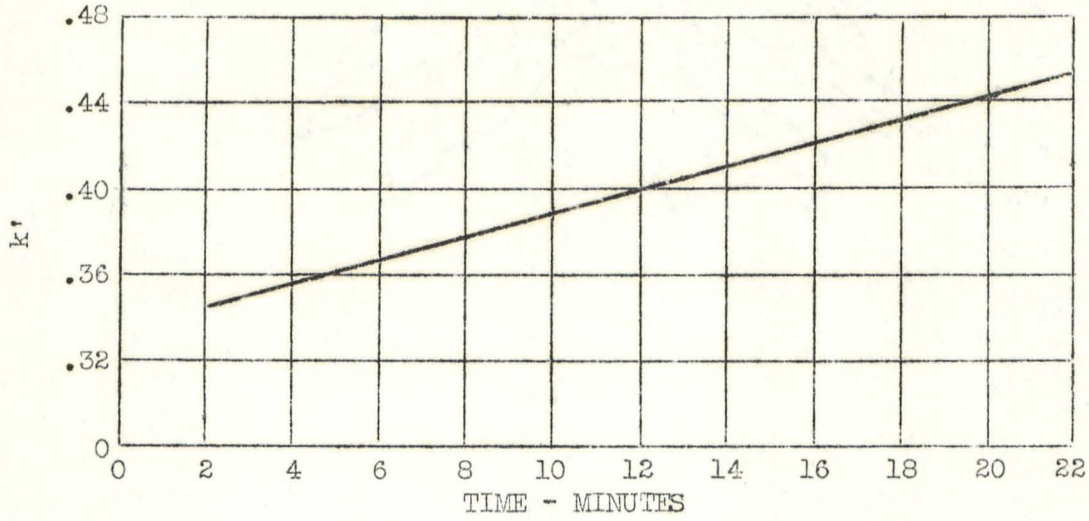

Figure 18.- Effect of time on constant k' in equation $p = 6.35 - k' M + k'' V + f(SV)$.

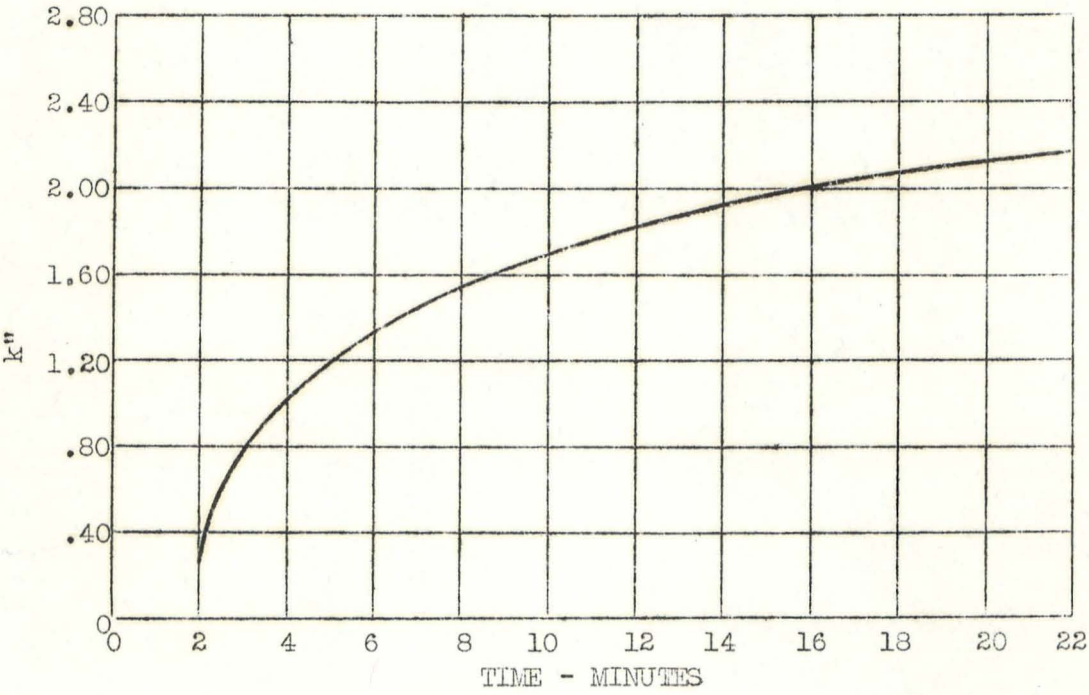

Figure 19.- Effect of time on constant k" in equation $p = 6.35 - k' M + k'' V + f(SV)$.

Table 3.- Values of k', k", K', and K", for calculating rate of perimeter increase and total perimeter, equations 3 and 4.

cumulated total of k' " " K"

Time minutes	k'	k"	K'	K"
2	0.35	0.26	0.69	0.52
3	.35	0.74	1.04	1.26
4	.36	1.00	1.40	2.26
5	.36	1.20	1.76	3.46
6	.37	1.33	2.13	4.79
7	.37	1.44	2.50	6.23
8	.38	1.53	2.88	7.76
9	.38	1.61	3.26	9.37
10	.39	1.68	3.65	11.05
11	.40	1.74	4.05	12.79
12	.40	1.80	4.45	14.59
13	.41	1.85	4.85	16.44
14	.41	1.89	5.26	18.33
15	.42	1.94	5.68	20.27
16	.42	1.98	6.10	22.25
17	.43	2.02	6.53	24.27
18	.43	2.05	6.96	26.32
19	.44	2.08	7.40	28.40
20	.44	2.11	7.85	30.51
21	.45	2.14	8.30	32.65
22	.45	2.16	8.75	34.81

The Effect of Slope

Inasmuch as forest topography is usually mountainous, and slope is recognized as an important factor in spread, this discussion would be incomplete without some consideration of the slope factor, which has been omitted up to this point mainly to simplify the problem. Studies of slope were conducted under both laboratory and field conditions. Field studies were in all respects similar to those described for fires on level ground.

In the study in the forest fire laboratory of the University of California a series of small fires were allowed to spread in a 4 by 10 foot burning pan at zero wind velocity and at slopes varying from 5 to 50 percent. Because of the small scale of the experiments, ponderosa pine needles were cut to a uniform length of $1\frac{1}{2}$ inches to produce a slow-burning, uniform fuel. It was impractical in these studies to measure perimeter increase, linear spread being used instead. Previous studies had shown that linear spread was closely related to increase in perimeter, and that generalizations true of one were applicable to the other.

The important contributions of the laboratory study were (1) an indication of the type of curve representing the effect of slope on increase on the longitudinal axis and (2) evidence that slope had apparently no effect on the spread of fire at right angles to the slope direction; these indications are illustrated in figures 20 and 21. This study did not result, however, in any quantitative evaluation of the relative effect of slope, moisture, and wind upon rate of spread.

The field study comprised 46 fires at slopes of 10 to 30 percent. These were too few to permit the type of analysis used in determining wind, moisture, and time relationships. It was decided, therefore, to determine the approximate relation of slope and perimeter through the use of the relationships already determined for fires on level ground, considering the deviations from the level ground perimeters as the influence of slope. When this was attempted, it was found that the size of the deviations depended largely upon the wind velocity at the period, or, in other words, that slope and wind were jointly correlated. Accordingly, the data were classified on the two variables, wind and slope, and deviations for each slope and wind velocity class determined. The resulting relationships are shown in figure 22.

It is apparent from a consideration of these curves that the influence of slope on rate of spread is inconsiderable at low wind velocities but that with higher wind, slope becomes increasingly important. The indicated increase due to slope may in many cases approach the original values on level ground. For instance, at moisture content of 5 percent, wind 4 miles per hour, and time 20 minutes, the rate of spread on level ground is 12.6 feet per minute. Under the same conditions but with a slope of 20 percent, the correction to be applied is 12.2 feet, resulting in a total indicated increase of 24.8 feet.

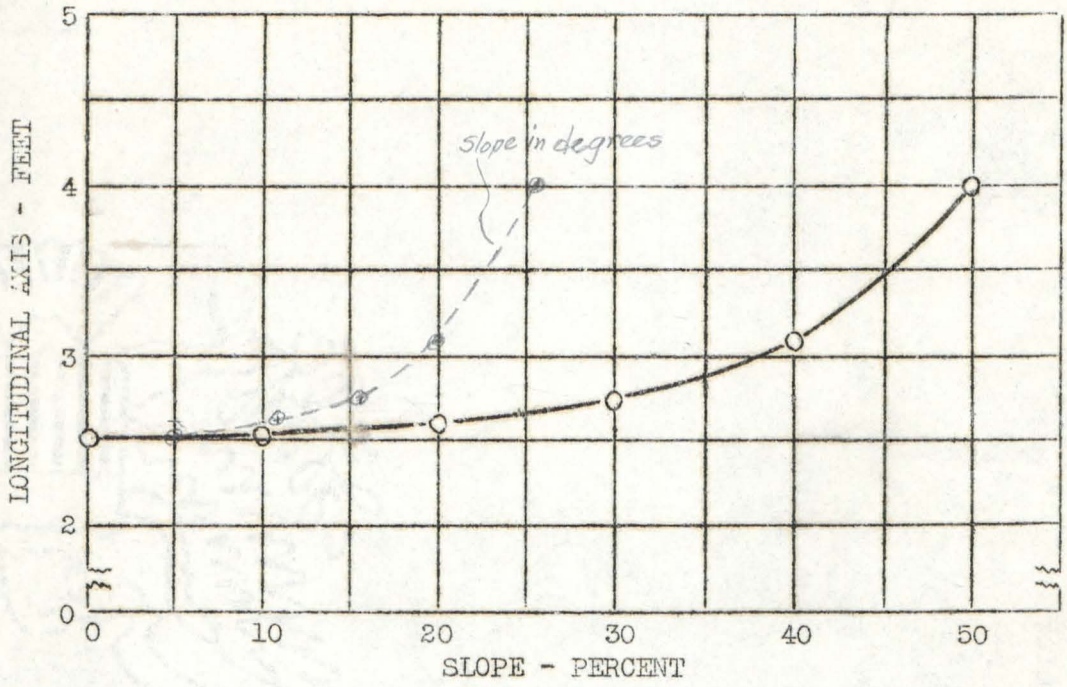

Figure 20.- Effect of slope on longitudinal axis of fires in feet at 3 minutes. Basis: 59 laboratory fires under constant moisture content and 0 wind velocity.

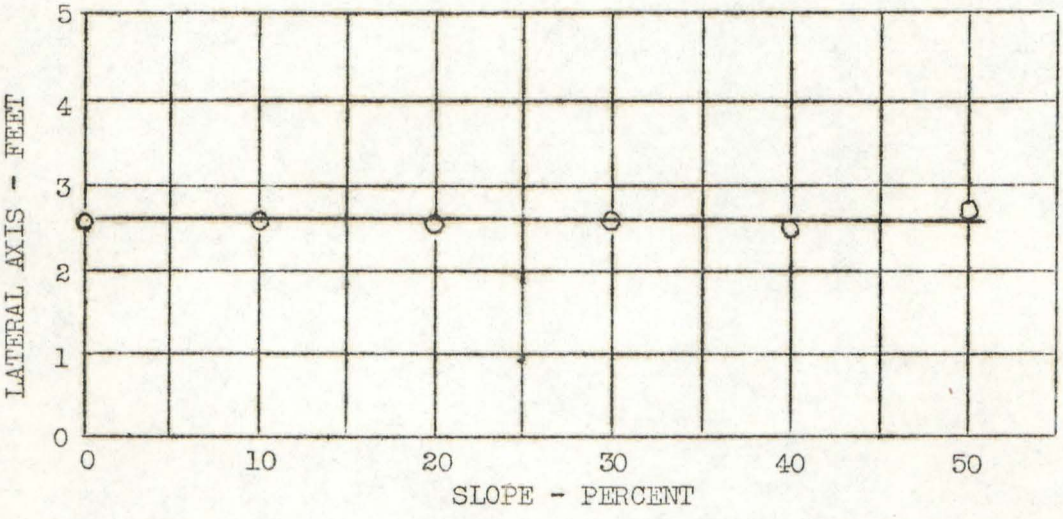

Figure 21.- Effect of slope on lateral axis of fires in feet at 3 minutes. Basis: 59 laboratory fires under constant moisture content and 0 wind velocity.

Value to be added to that for a level ground fire.

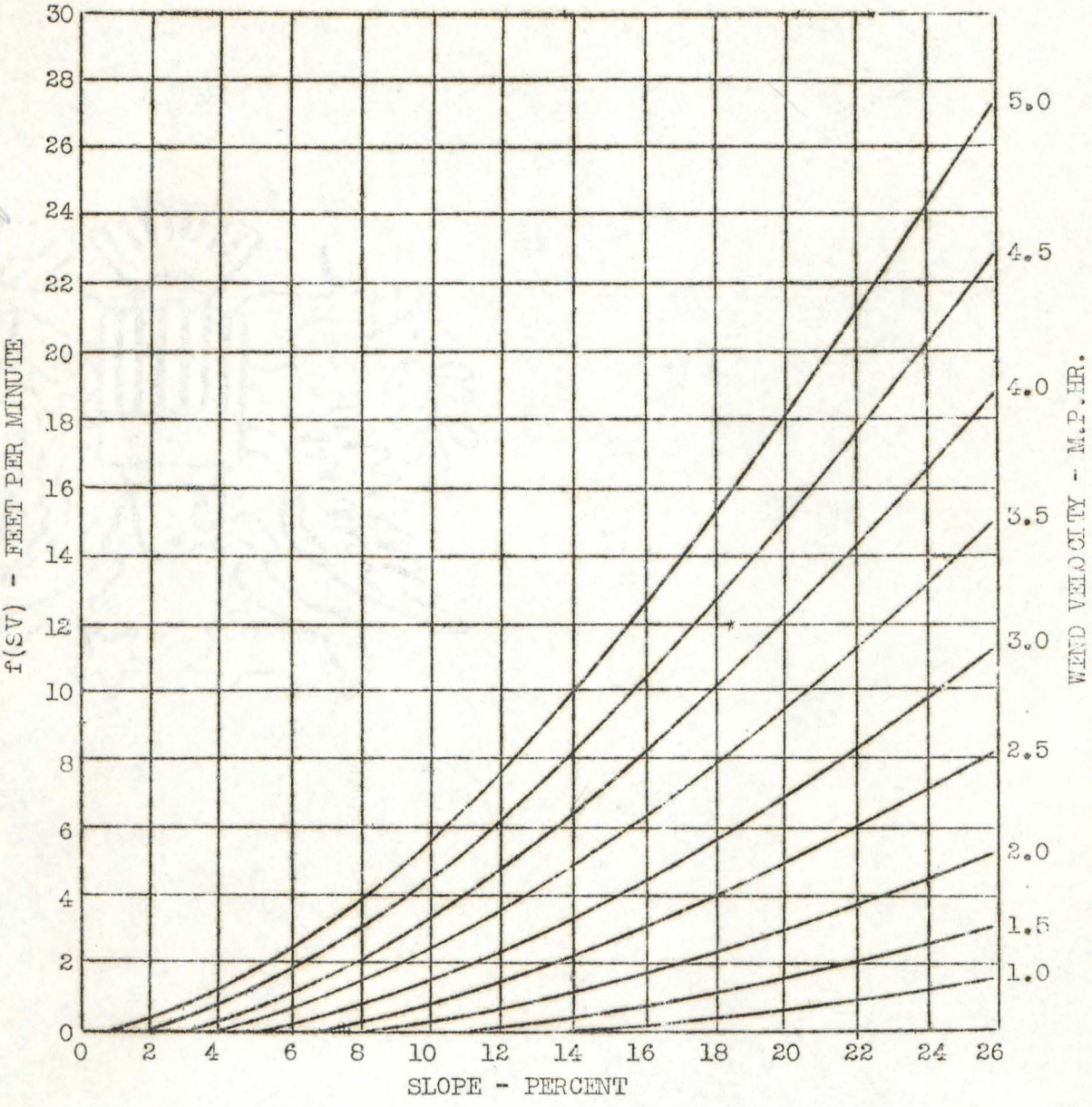

Figure 22.- Probable increase in rate of spread for slope fires over values for level ground for various slopes and wind velocities.

based on 46 fires 1934

The slope measurements used in the analysis were the slope percent in the direction of the greatest spread, which corresponded closely to the prevailing wind direction. The relationships shown on slope are based on relatively scant data and are therefore not of comparable accuracy to the wind and moisture curves.

As a result of the analysis explained above, equation 2 may now be rewritten:

perimeter increase in ft. per min.

$$p_t = 6.35 - k' M + k'' V + f(SV) \text{ ----------(3)}$$

Values of f(SV) may be obtained from table 4.

Estimating Total Perimeter

It is apparent that, for any values of wind and moisture within the range of data available, it is possible to calculate the total perimeter at any time interval up to 22 minutes from the relationships already explained and expressed in equation 3.

An equation to express total perimeter with constant wind and moisture conditions directly may be derived from equation 3, as follows:

$$P_t = 6.35t - (K_t')M + (K_t'') V + f(SV)t$$

in which P_t = total perimeter at a particular time; — not perimeter increase per min.
t = time in minutes from start of fire;
V = wind velocity in miles per hour;
K_t' = factor to be multiplied by moisture content (table 3);
M = moisture content in percent;
K_t'' = factor to be multiplied by wind (table 3);
$f(SV)$ = factor to be multiplied by time for slope fires (table 4).

The derivation of the above expression is as follows:

From equation 3, the perimeter at end of 2 minutes would be

$$p_2 = 2(6.35) - 2k_2' M + 2k_2'' V + 2f(SV)$$

and the perimeter increase in the third minute would be:

$$p_3 = 6.35 - k_3' M + k_3'' V + f(SV)$$

for the fourth minute,

$$p_4 = 6.35 - k_4' M + k_4'' V + f(SV)$$

and for the nth minute

$$p_t = 6.35 - k_t' M + k_t'' V + f(SV)$$

to be added to the rate of spread established for fire on level ground

Table 4.- Values of f(SV) for calculating rate of perimeter increase and total perimeter, equations 3 and 4.

V = Wind velocity in miles per hour:	S = Slope in percent					
	0	5	10	15	20	25
0	0	0	0	0	.1	.2
.5	0	0	0	0	.2	.5
1.0	0	0	0	.2	.6	1.2
1.5	0	0	.2	.7	1.6	2.8
2.0	0	0	.4	1.6	3.0	4.8
2.5	0	.1	.9	2.6	4.8	7.5
3.0	0	.2	1.6	4.0	7.0	10.5
3.5	0	.4	2.5	5.6	9.5	13.9
4.0	0	.8	3.4	7.3	12.2	17.7
4.5	0	1.3	4.5	9.2	15.0	21.6
5.0	0	1.8	5.6	11.2	18.0	25.8

Total perimeter at end of any time would be

$$P_t = p_2 + p_3 \text{ ---- } + p_t$$

Adding the above equations and factoring:

$$P_t = 6.35t = (2k_2' + k_3' + k_4' \text{ --- } k_t')M +$$

$$(2\,k_2'' + k_3'' + k_4'' \text{ --- } k_t'')\,V + f(SV)t$$

Let $K_t' = (2k_2' + k_3' + k_4' \text{ --- } + k_t')$ and

$K_t'' = (2k_2'' + k_3'' + k_4'' \text{ --- } + k_t'')$

Then, as already expressed,

$$P_t = 6.35t - (K_t')M + (K_t'')V + f(SV)t \text{ ----------(4)}$$

Values of K_t' and K_t'' have also been arranged in table 3.
Values of f(SV) have been arranged in table 4 for ease in computation.

To illustrate the manner in which total perimeter increases with time, figures 23 to 26 have been prepared. These figures illustrate the characteristic behavior noted by Show (6).

Accuracy of Estimate

To determine the accuracy of estimate of the relationships derived, 350 cases of rate of spread for a 2-minute period were drawn at random from the 1,153 cards for fires on level ground and compared to the original values. The results are as follows:

Fires on level

Average perimeter increases (feet)	11.4
Standard deviation of average (feet)	6.2
Standard error of estimate (feet)	4.3
Index of alienation	.69
Index of correlation	.72

As there were in all only 372 2-minute cases of fires on slopes, the entire sample was used in the computation of the measures listed below:

Fires on slopes

Average perimeter increases (feet)	22.9
Standard deviation of average (feet)	16.5
Standard error of estimate (feet)	12.7
Alienation index	.77
Correlation index	.64

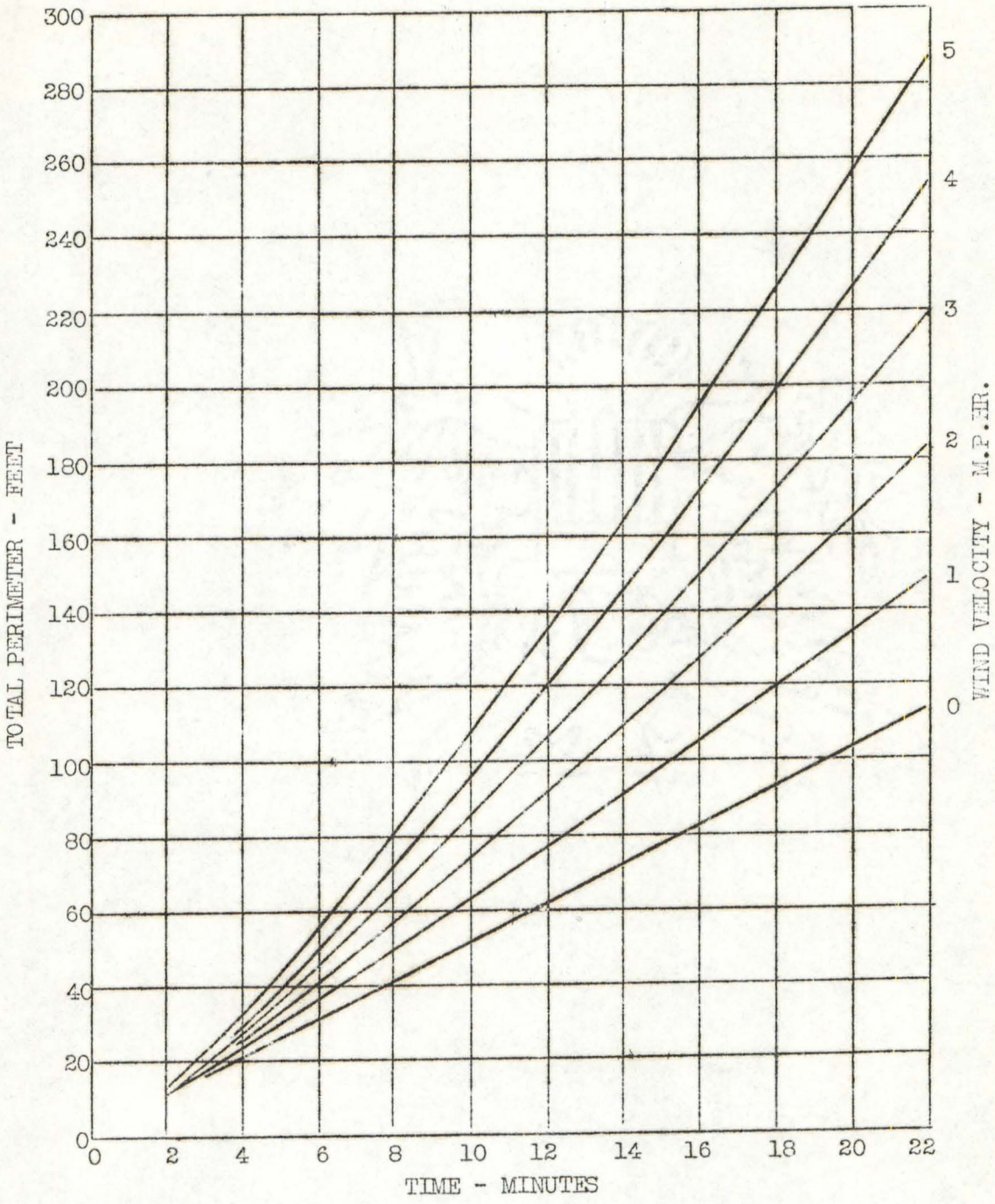

Figure 23.- Probable total perimeter of fires burning under various constant wind velocities at moisture content 3 percent.

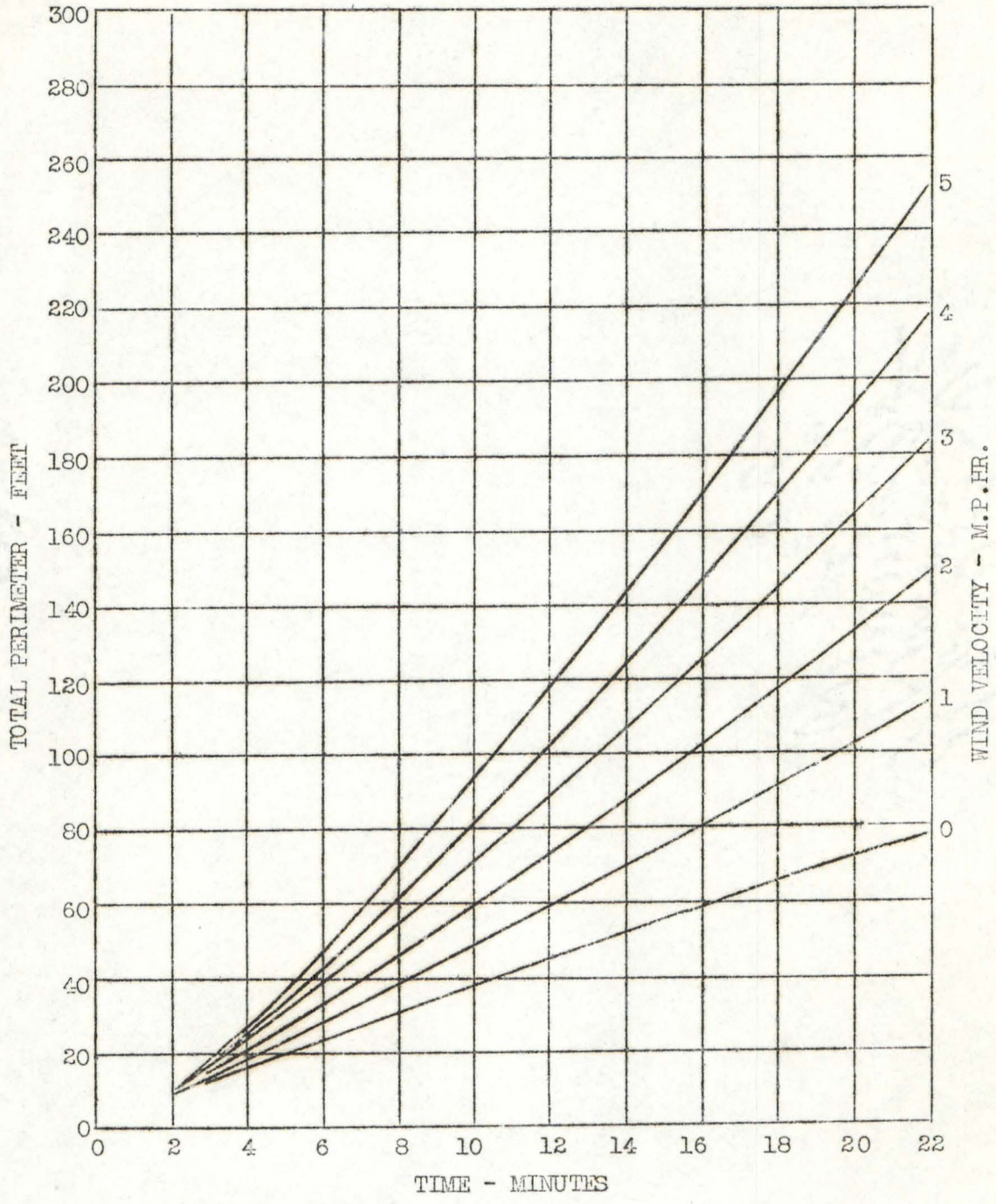

Figure 24.- Probable total perimeter of fires burning under various constant wind velocities at moisture content 7 percent.

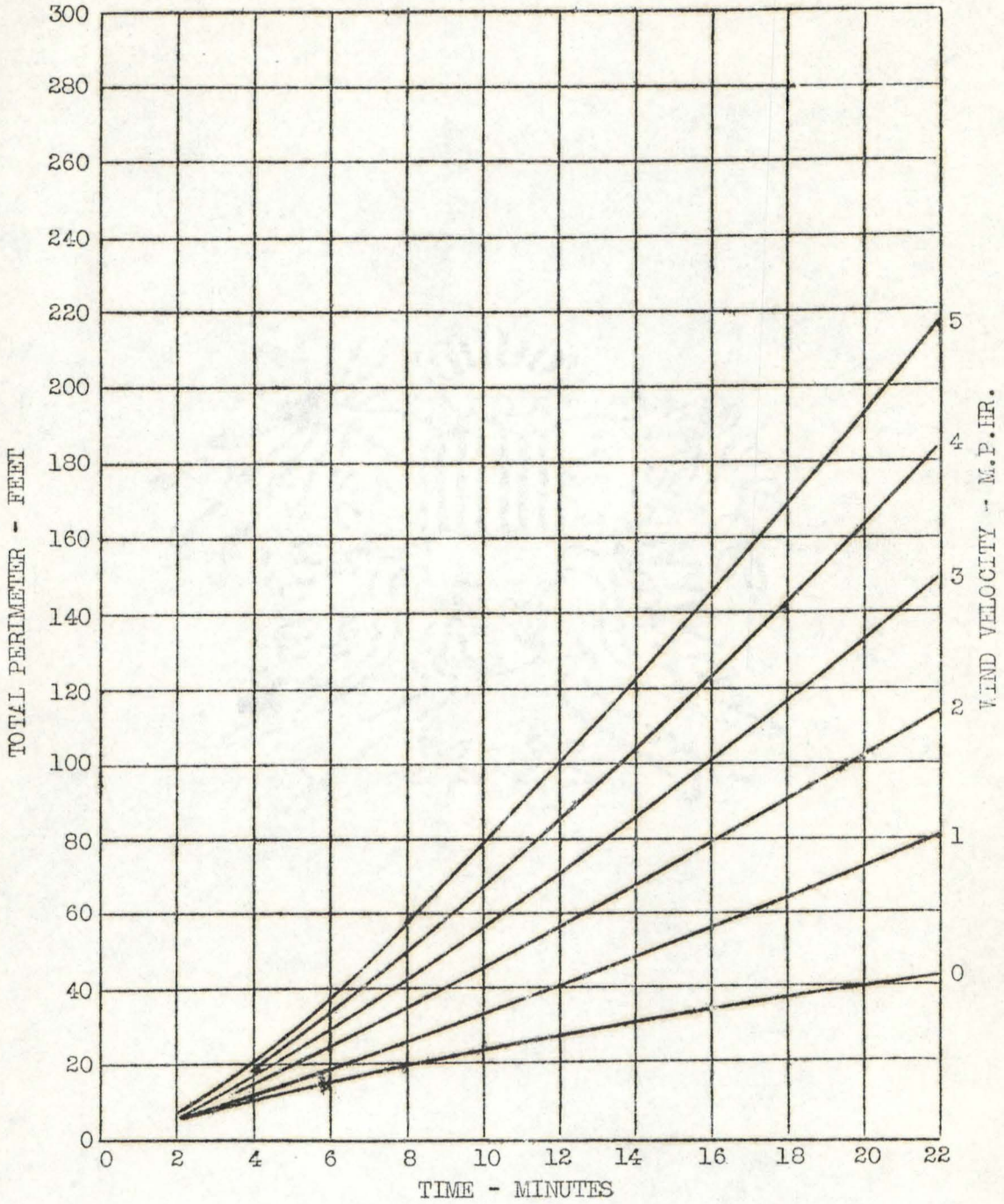

Figure 25.- Probable total perimeter of fires burning under various constant wind velocities at moisture content 11 percent.

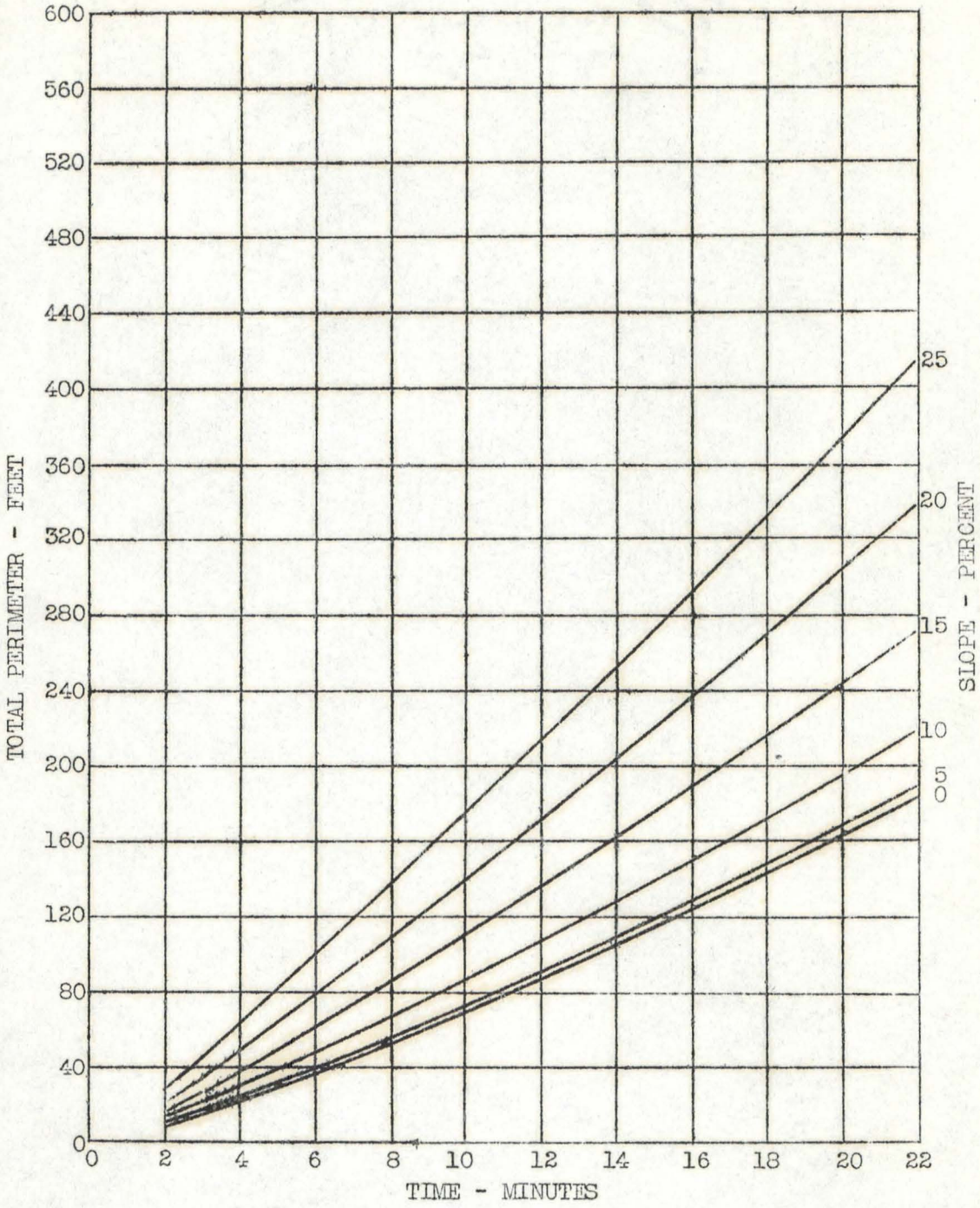

Figure 26.- Probable total perimeter of fires on various slopes for moisture content 7 percent and wind velocity 3 m.p.hr.

The absence of higher correlation is due in part to error in the measurement of perimeter, moisture, and wind. On a fast-burning fire it is impossible to approximate the location of the line closer than one foot, and this error is magnified in terms of perimeter. Measurements of moisture are only average values and cannot be expected to approximate closely the moisture content of the particular portion of the litter in which the fire is spreading at a given time interval. Measurements of wind velocity may also fail to show accurately the wind movement near the head of the fire. These errors are not cumulative but compensating and greater correlation may accordingly be expected when the relationships are used in the estimation of total perimeter. That much higher correlation results in these circumstances is shown by table 5, in which indexes of correlation have been derived for each 2-minute period from a comparison of the estimated and actual total perimeters. Table 5 also gives comparisons of actual and estimated perimeters on slope.

The measurements indicate that, although it is not possible to estimate rate of perimeter increase with a high degree of accuracy, yet when the relationships derived are applied to estimates of total perimeter, high correlation and satisfactory estimating accuracy result. In general the relationships derived appear to be substantially confirmed by these measures of correlation.

SUMMARY

In this study of rate of spread of small surface fires in selected even-aged second-growth stands of P. ponderosa, records were analyzed of about 160 fires with burning periods of 16 to 22 minutes.

The influence of both moisture and wind is described as linear, with the slope of the curves varying with the time factor. Where fires burned with low wind, the maximum rate of spread as controlled by the moisture content was soon attained. With higher velocities, the period required to attain maximum spread increased, and in some cases exceeded the limits of the data.

The effect of slope on rate of spread was found to be curvilinear, and largely dependent for its influence upon the occurrence of winds in the direction of the slope.

Empirical formulae derived from the smoothed curves permit estimates of rate of perimeter increase or total perimeter at any time interval within the limits of the data. The generalizations made appear highly significant, and estimates of total perimeter may be made within a satisfactory standard error.

Extension of rate-of-spread studies to other types is dependent to a large extent upon research leading to methods of evaluation of the factor of fuel variation. With progress in present studies of fuels, similar studies in more complex forest types are contemplated.

Table 5.- Summary of results in the application of the derived relationships to the computation of total perimeter of test fires on level and sloping ground at each 2-minute time interval from start of fire.

Time in minutes	Cases	Average perimeter		Standard deviation of average actual perimeter	Standard error of estimate		Alienation index	Correlation index
		Actual	Calculated					
	Number	Feet	Feet	Feet	Feet	Percent		
Fires on level ground								
2	118	7.5	7.6	2.6	2.1	28.0	0.81	0.59
4	118	17.7	17.7	6.4	4.5	25.4	.70	.71
6	118	28.9	28.6	9.8	6.2	21.5	.63	.78
8	118	40.0	40.0	15.0	9.4	23.5	.63	.78
10	118	51.2	51.6	18.6	11.1	21.7	.60	.80
12	117	63.5	63.0	22.6	13.7	21.6	.61	.79
14	114	75.4	74.7	27.1	16.0	21.2	.59	.81
16	109	87.0	86.1	31.5	16.5	19.0	.52	.85
18	96	97.7	96.5	38.9	19.2	19.7	.49	.87
20	71	102.3	102.8	40.9	17.2	16.8	.42	.91
22	56	112.6	112.6	51.2	19.7	17.5	.38	.92
Fires on sloping ground								
2	46	12.1	15.5	7.2	6.8	59.4	.94	.34
4	46	32.4	34.9	18.5	10.2	40.7	.55	.83
6	46	58.5	57.4	33.2	18.4	33.4	.55	.83
8	46	87.2	82.8	52.1	30.4	32.8	.58	.51
10	42	105.5	102.4	64.5	38.5	32.7	.60	.80
12	36	116.2	122.2	50.0	35.5	30.5	.71	.70
14	31	128.1	139.8	52.5	37.8	30.5	.72	.69
16	27	144.3	166.3	59.5	41.6	30.2	.70	.71

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